NASA-CR-197792

IN-STEP PHASE A VOLUME I TITLE PAGE

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43545

Experiment Title: (Proposed title - use no acronyms)

Micron Accuracy Deployment Experiment (*MADE*)

Proposing Organization(s):

The Regents of the University of Colorado
Department of Aerospace Engineering Sciences
Center for Space Construction

NASA Langley Research Center
Structural Mechanics Branch

Payload Systems Inc.

Principal Investigator:

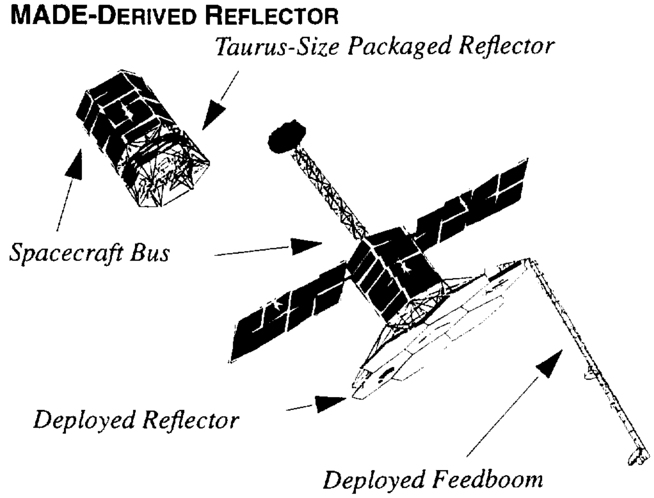
Prof. Lee D. Peterson, Principal Investigator, University of Colorado
Dr. Mark S. Lake, Co-Principal Investigator, NASA Langley Research Center

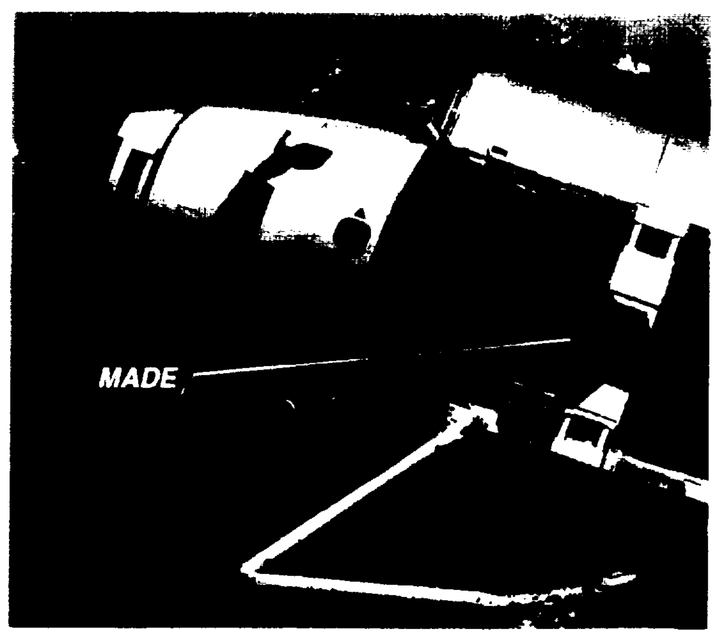
Experiment Summary: (Describe experiment, objectives and potential benefits in 250 words or less)

The University of Colorado, NASA Langley Research Center and Payload Systems Inc., stand ready to deliver an aggressive, breakthrough technology experiment entitled *MADE* for Micron Accuracy Deployment Experiment. In a single validation flight, this team will increase the precision of deployable instruments by at least a factor of fifty. Using *MADE* technology, precision instruments from sub-millimeter to optical can be routinely and reliably deployed from compact spacecraft. No other existing technology can accomplish this.

By deploying a portion of a micron-precise 3.5 meter reflector from the Shuttle payload bay, *MADE* will validate technology which enables the deployment of spacecraft instruments to five microns accuracy with one micron stability. The key is an innovative, inexpensive zero-freeplay revolute joint with less than three microns hysteresis over a 100 pound load range *and* less than 0.5 inch-oz. of friction.

NEW-MILLENNIUM SIZED SPACECRAFT USING A MADE-DERIVED REFLECTOR





Phase A micro-mechanical ground tests predict that future *MADE*-derived deployable instruments could be preconfigured on the ground to within five microns of their deployed, on-orbit positions. Flight confirmation of these results and the timely application of the science are required before *MADE* technology can be applied to production spacecraft.

MADE is essential technology for the NASA New Millennium initiative, which seeks to save science mission cost by packaging spacecraft into inexpensive expendable launch vehicles. Furthermore, because the *MADE* team actively involves end-users such as Lockheed-Martin, TRW, AEC-ABLE, and Teledesic, *MADE* helps create new billion-$ markets in orbital telecommunications and resource mapping.

IN-STEP PHASE A SUMMARY FORM 1

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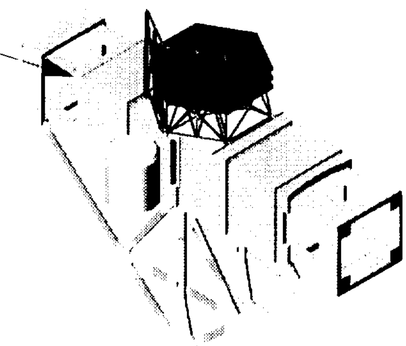
Experiment Title:

Micron Accuracy Deployment Experiment (*MADE*)

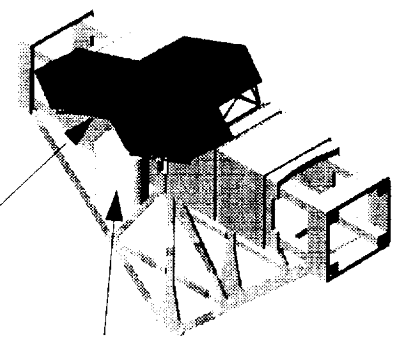
MADE WILL TEST THE MICRON-LEVEL 0-G GEOMETRIC ACCURACY OF A REPEATEDLY DEPLOYED REFLECTOR

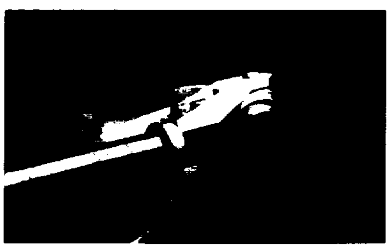
"FLIGHT VALIDATED, LOW-COST, RELIABLE DEPLOYMENT TO FIVE MICRONS PRECISION"

- *MADE* will be repeatedly deployed from the top of a MPESS platform in the Shuttle payload bay.
- *MADE* will use new high precision low friction joints shown to have less than three microns hysteresis as part of the Phase A testing program. (See Section 2.1.3, page 11.)

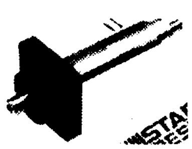


- *MADE* will validate the Phase-A scientific ground data that has lead to a new theory of how mechanically deployable structures behave at the micron-level of motion in 0-g. (See Section 2.1.4, page 13).





- *MADE* will use non-pyrotechnic, flight-proven paraffin-energized actuators and latches. (See Section 2.1.2, page 10.)
- *MADE* will measure the deployed structure's shape using a low-cost imaging system with a Phase-A validated resolution of 0.37 microns at a three meter standoff. (See Section 2.4.4, page 18.)
- *MADE* data will be collected using technology from Payload Systems Inc. that has been flown on several previous Shuttle In-STEP experiments. (See Section 2.4.4, page 18.)



- *MADE* will validate the hypothesis that *MADE*-derived, deployed spacecraft components can be preconfigured on the ground to within five microns of the on-orbit position by exploiting the micro-mechanical lurching of the structure on-orbit.
- The micro-mechanical engineering science data collected from *MADE* and the hardware developed in the *MADE* program will directly impact NASA science missions, especially small-spacecraft initiatives such as New Millennium.

Provide a diagram and description of the experiment above

	Phase B	Phase C/D	Total (all Phases)
Cost ($K):	$823.3	$4108.9	$4932.2
Duration (Months):	10	32	42

IN-STEP PHASE A SUMMARY FORM 2

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Experiment Title:

Micron Accuracy Deployment Experiment (*MADE*)

Experiment Objectives (Provide concise statements of main objectives in bullet format):

MADE's Objective is to validate technology for deploying spacecraft instruments to within 5 microns of the ground-adjusted position with 1 micron of on-orbit positional stability. To do this, *MADE* will both demonstrate function and collect engineering data as follows:

- Deploy a portion of a 3.5 meter reflector consisting of a deployed metering truss, a center panel, and two deployed panels from the Shuttle payload bay. Use very linear, low-friction joints based on preloaded roller bearings.
- Verify the hypotheses that discrete points on the deployed configuration migrate under the successive application of impulsive loads to a zone 5 microns wide. Verify that gravity moves the equilibrium zone less than 1 micron.
- Verify that the final resting place is stable within the equilibrium zone to within 1 micron under a 50 pound impulse.
- Characterize how the migration depends on force amplitude and location. Characterize how the transient micro-lurch depends on the participation of individual vibration modes.

Justification for Space Flight (bullet format):

- *MADE* will collect data available only in 0-g to verify and understand the micron-level behavior predicted above. When compared with ground-based analysis and tests, these results can be extended to any future application of *MADE* technology.
- This data cannot be collect in 1-g because of gravity preload on the fixtures and supports.
- Without the long-duration 0-g data collected by *MADE*, the very promising results predicted from Phase A measurements cannot be applied to future spacecraft. With *MADE*, the flight-validated state-of-the-art will advance by more than a factor of 50.

Experiment Benefits (Also indicate benefits over competing technologies, in bullet format):

- *MADE* will enable the micron accurate deployment of large aperture scientific and communications instruments from small, low cost launch vehicles.
- No other technology, existing or proposed, can approach the 5 microns of precision the *MADE* program has *already achieved* in Phase A ground tests. Competing concepts, such as inflatables, are inherently limited to 1,000 microns precision. Competing mechanisms have achieved no better than 250 microns of precision.
- Once flight-validated, *MADE* will provide much needed technology to scientific and commercial customers. The combination of flight and ground testing in the *MADE* program will enable the compact packaging of many future science spacecraft.
- *MADE* provides urgently required, quantifiable confidence in precision deployables for NASA scientists, designers and program planners by repeatedly deploying the test article on orbit and measuring its sub-micron behavior.
- *MADE* is a model team effort that exploits complementary capabilities at the University of Colorado and NASA Langley. The synergism between CU's basic research program in nonlinear structural mechanics with Langley's applied research program in aeronautical and astronautical structures, will ensure that the *MADE* flight test results will find the broadest possible impact.

Applications To Future Space Missions (bullet format):

MADE's customers and end-users have helped define flight objectives to ensure the relevancy of *MADE* to the following missions:

NEW MILLENNIUM. Precision deployment of compact instruments is perhaps the single most challenging part of the New Millennium initiative. Only *MADE* can provide flight validated technology in time to impact New Millennium spacecraft, and it does so with innovative, low cost solutions.

OTHER NASA SCIENCE MISSIONS. By reducing the spacecraft and booster size while preserving science capability, *MADE* could also reduce the costs of the following NASA Code S and Code Y missions:

- AIM/OSI
- FUSE
- FIRST
- EOS
- TOPSAT

COMMERCIAL MISSIONS. *MADE* technology will enable new, perhaps multi-billion dollar commercial markets in:

- Submillimeter (300 GHz+) mobile communications
- Orbital imaging and resource mapping
- Orbital internet (Teledesic II)

BY FUNDING MADE, NASA WILL OPEN NEW US COMMERCIAL MARKETS WHILE MAKING NASA SCIENCE MISSIONS CHEAPER.

VOLUME I: TECHNICAL PLAN FOR THE MICRON ACCURACY DEPLOYMENT EXPERIMENT (*MADE*)

1.0 RELEVANCE AND TECHNICAL MERIT

In the next ten years, the possibility of an extensive orbiting information gathering and distribution system has the potential to revolutionize not only our science but also our way of life. The catalyst of this revolution is exciting, breakthrough technologies that promise to enable vastly more efficient and cheaper spacecraft and science instruments to be launched at markedly lower costs using small expendable launch vehicles. Already, NASA is heralding the coming of this new age of space operations with the innovative "New Millennium" initiative. Because it marries the science users and spacecraft technologists in a joint endeavor, New Millennium will develop breakthrough technology and rapidly infuse it into revolutionary new science missions.

By deploying compact instruments from micro-sized New Millennium spacecraft, it will be possible to discover planets around near-by stars, make detailed surveys of near-by planets, and make critical measurements of the health of our own, all within the constraints of modern fiscal reality. With the same technology, commercial ventures can be launched that sell valuable earth resource surveys and distributed high speed networks from space. Emerging technologies in submillimeter communication from the defense sector will make it possible to transmit video, data, images, and voice from low cost mobile communicators. In these ways, the micro-sized spacecraft of the New Millennium initiative will fundamentally change our access to and our use of space.

But while much needed attention has recently been paid to the electronic, computational, and systematic requirements of these spacecraft, a major technical requirement has been largely ignored. Reducing the size of these spacecraft will save both on launch costs and system complexity, but functionality must be preserved. This will mean deploying or unfolding some of the instruments to increase the aperture or the resolution of the sensor system. Consequently, future spacecraft, even more so than spacecraft in the past, will depend on the deployment of precision instrument components such as parabolic reflectors, sensor arrays, and optical platforms. For these devices to function properly, their geometric shape and arrangement must often be configured to within a few microns or less.

No technology comes close to fulfilling this requirement. The University of Colorado (CU), NASA Langley Research Center (LaRC), and Payload Systems Inc. (PSI), propose the Micron Accuracy Deployment Experiment (*MADE*), an aggressive, breakthrough flight validation experiment which will substantially fill this technological void.

In a single experimental flight, *MADE* will validate technology that enables the automatic deployment of spacecraft components to within 5 microns of the ground-adjusted position with 1 micron of long-term stability. This is at least 50 times more precise than any existing deployment technology. Only a technical leap of this magnitude will meet the precision requirements of future science users.

Because companion technologies in control-structures interaction (CSI) and active optics can remove the effect of any remaining static and dynamic imprecision, *MADE* will make the deployment of optical instruments as routine as the deployment of a microwave communications antenna. For example, it will be possible to use *MADE* technology to deploy an interferometer with the resolution of the Hubble from a Taurus class launch vehicle for a fraction of the cost. Without *MADE*, this cannot be done.

The ability to precisely deploy science instruments from a lightweight compact package is possibly the single most important technical hurdle facing the New Millennium and other satellite miniaturization initiatives. No other potential In-STEP experiment has as broad a range of critical impact. But to understand this potential relevance, it is necessary to first review the needs of customers for precision deployment technology, the engineering problem of precision deployment, and the solutions offered by *MADE*. This is done in the next several sections.

1.1 CUSTOMERS REQUIRE MICRON PRECISION DEPLOYABLE SPACECRAFT TECHNOLOGY

MADE technical requirements are strongly driven by the needs of targeted customer applications. In fact, substantial technology advances made during Phase A allowed us to increase our target precision from 50 microns to 5 microns and accommodate a much broader range of customers. This section reviews the traceability of these requirements.

1.1.1 Why Do Science Users Need Micron Precision?

SCIENCE INSTRUMENTS RELY ON SEPARATION OF COMPONENTS TO MICRON PRECISION FOR SENSITIVITY AND RESOLUTION.

All electromagnetic instruments require the collection and assemblage of light energy into a sensor array. This can be as simple as the reflection of microwaves from a mesh antenna onto a phased array collector, or it can be as exotic as the focusing of ultraviolet photons into an astrometric interferometer. In both cases, the quality of the instrument is affected by how accurately the sensing elements are positioned with respect to each other, but the actual requirement varies from application to application. For most applications, this error needs to be less than perhaps 2% of a wavelength of light being sensed. Figure 1 illustrates this by comparing flight qualified and engineering model technologies against the requirements of example missions. Note the large gap between flight qualified technologies and the requirements of future missions. In this context, *MADE* is an enabling technology because it is a significant advancement in the state-of-the-art.

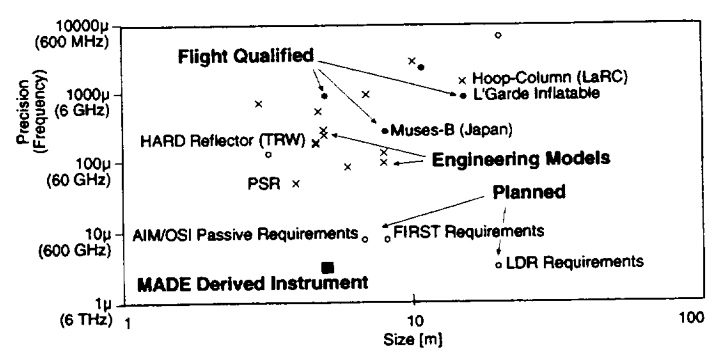

FIGURE 1. ***MADE* will enable a level of precision that meets or exceeds the requirements of currently planned missions, and is several orders of magnitude above competing flight qualified technology.**

So long as instrument components are rigidly fixed to a spacecraft bus, it is relatively straightforward to adjust their orientation to a few microns and, if needed, to within a few nanometers. In fact, this is how adaptive optics systems, including for instance high precision structural control systems and variable baseline interferometers achieve nanometer accuracy. Active optics can accommodate a large range of dynamic motion error, but not without loss of performance. Both CSI and active optics rely on the presumption that the spacecraft bus is quasi-statically solid and stable at least to a moderate level of dynamic range. While the required structural precision varies from system to system, the following generalizations can be made:

- Active optics systems and layered precision CSI expect their spacecraft components to be oriented to within 10 microns of their expected position and stay linear to within 1 micron of this position.
- Any increased precision in the static position of the structural components relaxes the requirements on active components, which means either better performance or lower cost.

1.1.2 How Does Deployment Affect Mission Cost?

THE NEED TO DOWNSIZE CODE S AND CODE Y MISSIONS TO SMALLER LAUNCH VEHICLES WITHOUT LOSS OF SCIENCE URGENTLY DEMANDS *MADE* TECHNOLOGY.

One solution to precision configuration of a spacecraft sensor system is to avoid deployment by adjusting all components on the ground and making them sufficiently rigid to remain in place under launch loads (typically 11 g dynamic overstress on unmanned vehicles). This has two system-wide impacts:

- Launch vehicle size can be more determined by the diameter of the instrument than by the mass of the spacecraft.
- Cost limits directly limit the science capability because larger instrument sizes are too expensive.

While the cost impact associated with increasing the size of the launch vehicle is difficult to quantify except on a case-by-case basis, millions of dollars in launch cost might be saved by fitting payloads inside smaller shrouds. During *MADE*'s Phase A effort, the *MADE* team contributed to a redesign of the Far Ultraviolet Spectroscopy Experiment (FUSE). Without sacrificing instrument performance, *MADE* technology would have packaged FUSE into a Taurus sized launch vehicle instead of the intended Delta class vehicle. *If MADE had been flown, over $30M would have been saved in this case alone.*

1.1.3 Why Isn't Precision Deployment Used Routinely?

PAST RESEARCH IN DEPLOYABLES HAS FAILED TO ADDRESS FUNDAMENTAL ENGINEERING ISSUES THAT DEFINE THEIR RELIABILITY AND CAPABILITY FOR PRECISION DEPLOYMENT. *MADE* WILL EXPOSE AND RESOLVE THESE ISSUES, THUS SHATTERING EXISTING PARADIGMS AND RENEWING CONFIDENCE IN THE USE OF PRECISION MECHANICAL DEPLOYABLES.

There is a deserved perception among scientists and sensor engineers that the precision mechanical deployment of large pieces of a spacecraft is at best risky and at worst a formula for disaster. The objections are:

- Mechanisms do not work in space.
- Precision means mechanisms must be tight, which means they might bind. Thus, precision means low reliability.
- It is preferable to relax science requirements rather than to use a deployment scheme.

To resolve these problems, NASA has supported research to improve the reliability and capability of deployable systems. For instance, there is an existing In-STEP flight experiment in Phase C intended to assess the precision of a deployed inflatable reflector. If successful, this experiment may lead to replacement of mesh antennas for spaceborne communications.

While such an approach may be adequate for 1000 micron-class deployment and for solar panel deployment, it is not applicable for frequencies above 20 GHz and is certainly inappropriate for optical instruments. This is supported by examining the basic physics and mechanics required of inflatable materials. Packaging an inflatable without inducing a permanent crease several hundred microns high can only be done if the strain-to-yield of the material is very high, approximately that of polymer materials. But, at the same time, to preclude thermal and dynamic disturbances, inflatables must have approximately the stiffness-to-mass ratio and the coefficient of thermal expansion (CTE) of composites. No known or proposed material has this combination of properties.

1.2 *MADE* REVOLUTIONIZES RELIABLE, PRECISION DEPLOYMENT WITH A LOW-COST, BALANCED, RATIONAL APPROACH

To enable both high-precision and high-reliability deployment, the *MADE* team has adopted an approach that balances cost/risk against system capability. This approach requires a distinction to be made between *kinematic precision* and *absolute precision*.

Absolute precision is defined as the absolute deviation of a structure from its theoretically exact shape. A *predictable* structure is defined as one whose absolute precision can be accurately predicted by superimposing mechanical distortions (thermal, hygroscopic, and static and dynamic load response) over the measured fabrication errors.

Kinematic precision is defined as geometric variability due to deadband in a structure. Deadband includes freeplay or hysteresis in joint mechanisms, and allows small-magnitude deformations without static loads developing in the structure. In general, kinematic errors are probabilistic and unpredictable.

1.2.1 Is it Possible to Actively Control Any Structure to Any Arbitrary Precision?

ARBITRARY PRECISION IS ONLY THEORETICALLY ACHIEVABLE IF ZERO-STIFFNESS KINEMATIC ERRORS ARE ELIMINATED.

Figure 3 illustrates how the magnitude of various error sources determine the type of shape compensation that can be used. If the sum of all errors (fabrication, mechanical, and kinematic) is below the total error budget, the structure is *passively* precise. Fabrication (or quasi-static mechanical) errors that exceed the absolute error budget, can be corrected using quasi-static or *adjusted* shape control. Dynamic mechanical errors that exceed the absolute error budget can be corrected using *active* shape adjustment. However, if kinematic errors exceed the absolute error budget, the structure's shape *may not be correctable with any active control*

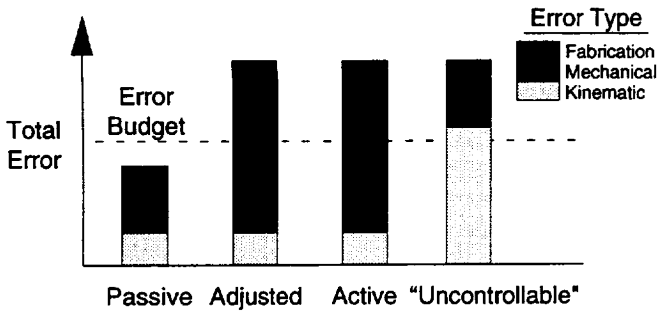

FIGURE 2. Error sources and their affect on shape control.

scheme. For instance, deadband or joint freeplay is a zero-stiffness nonlinear phenomenon, and control structure technology has not been demonstrated to apply for such structures. However, it is likely that kinematic errors due to hysteresis are controllable, as long as the mechanics are largely linear.

Traditional (passive and adjusted) deployable structures either have significant kinematic errors due to hinge freeplay, or they incorporate post-deployment preloading devices to eliminate freeplay. Inevitably, these devices add complexity, mass, and cost to the structure. Generally, these devices also increase deployment risk because they substantially increase deployment forces and complicate or prohibit re-stowage or reconfiguration after initial deployment. Also, post-deployment preloading induces global mechanical strains and deformations that are difficult to predict - especially if the structure is indeterminate.

1.2.2 How can High-Precision be Achieved with High-Reliability and Low-Cost?

RELIABILITY AND PRECISION CAN BE BALANCED BY MINIMIZING KINEMATIC IMPRECISION, USING ADAPTIVE ADJUSTMENT AND ACTIVE CONTROL WHEN NECESSARY, AND DOING SO WITH LOW FRICTION JOINTS.

Consider the cost versus absolute precision of adaptive shape adjustment. In general, the lowest cost (risk) system is *passive*. However, there is a limit below which passive precision is not possible due to fabrication tolerances and material thermal and hygroscopic stability. Trade studies of cost (risk) versus performance show that different realms of absolute precision can be defined in which each approach (active, adjusted, and passive) provides lowest overall cost. Figure 3 illustrates this trade-off.

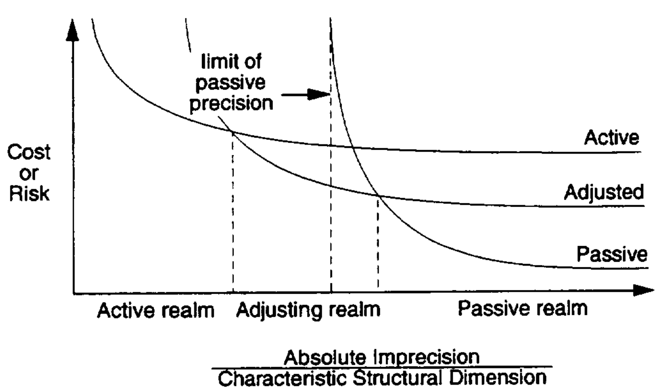

FIGURE 3. *MADE* validates technology which balances actively controlled with passive kinematic precision to achieve minimum cost and risk.

Although the function describing minimum cost (risk) versus absolute precision is different for each application, some principles can be applied in all cases to achieve minimum cost (risk):

- Adaptive control of any type is substantially less risky if the system is deterministic - *kinematic error sources should be eliminated, and the structure should be linear.*
- If absolute precision cannot be achieved passively and adaptive control is to be incorporated, *total cost can be reduced by relaxing fabrication tolerances and compensating with one-time shape adjustment after assembly, again provided the structure is linear.*
- Absolute precision is maximized and cost (risk) of adaptive adjustment is minimized if mechanical errors are minimized. This means one should *use high-stiffness, stable materials along with efficient (high stiffness/weight) structural architectures.*
- Reliability is maximized by minimizing the friction in deployment mechanisms and by simplifying the kinematics of the deployment process.

MADE **ENABLES LOW-COST, HIGH-RELIABILITY, HIGH-PRECISION DEPLOYMENT BY ELIMINATING KINEMATIC ERRORS WITHOUT EXCESSIVE FRICTION AND BY PROVIDING A LINEAR AND PREDICTABLE DEPLOYED STRUCTURE WITHOUT POST-DEPLOYMENT PRELOADING.**

1.3 *MADE* PRODUCTS ARE BREAKTHROUGH TECHNOLOGY REQUIRING FLIGHT VALIDATION

1.3.1 What are *MADE*'s Products?

MADE will fundamentally change the state-of-the-art in precision deployable spacecraft components, thus enabling new and heretofore inaccessible commercial markets and spacecraft missions. *MADE* is not an incremental technical change or incremental engineering improvement. Rather, it validates the following breakthrough component technology:

- Roller-bearing-based precision joints with less than 3 microns of hysteresis over a 100 pound load range and an extremely low thermal expansion coefficient (10^{-7}).
- Kinematically simple deployment concepts powered by reliable, compact DC-powered actuators delivering 50 in-lb of useful force in a 40 gm package.
- An inexpensive space-rated metrology system with 0.1 microns of resolution, 4 mm range, and 3 meters standoff
- A ground-based pre-flight adjustment methodology which can be used to configure precision components for 0-g deployment to within 5 microns of the desired position.

1.3.2 How Do these Help Scientists and Spacecraft Instrument Designers?

FOR END USERS, THIS MEANS THAT THE STRUCTURE BEHIND THEIR INSTRUMENT WILL BE JUST AS RIGID AND DEPENDABLE WHETHER IT IS DEPLOYED ON-ORBIT OR RIGIDLY ASSEMBLED ON THE GROUND. THIS IS THE FUNDAMENTAL CONTRIBUTION OF *MADE*.

1.4 *MADE* TECHNOLOGY IS CRITICAL TO FUTURE NASA SCIENCE MISSIONS

MADE technology will have a broad and important impact to future NASA science missions. This relevance is summarized in the following sections. Even before flight, the *MADE* team has been proactive in applying *MADE* technologies to NASA needs. As an example, *MADE*'s breakthrough metrology system may already have found application to another important NASA program. *MADE* researchers have been approached by the Photogrammetric Appendage Structural Dynamics Experiment (PASDE) to apply *MADE*'s state-of-the-art image processing algorithm to provide a 5-fold increase in resolution for motion in this experiment. PASDE seeks to measure the transient vibration of the MIR solar arrays during a Space Shuttle docking later this year.

1.4.1 Will *MADE* Benefit New Millennium Missions?

***MADE* IS PRIMARY NEW MILLENNIUM TECHNOLOGY.**

NASA is at the threshold of a new era in spacecraft design and operations. Billion-dollar science missions, characteristic of the past two decades, have been all but eliminated from the manifest. In their place, New Millennium class missions are being planned that will cost one to two orders of magnitude less and will fly only two or three years after inception. These missions form the centerpiece of all NASA spacecraft technology development for the coming decade.

During recent New Millennium workshops, science users from NASA's Code S and Code Y outlined "tall-tent-pole" technologies that they consider necessary and enabling for New Millennium class missions. Recognizing that the move to smaller launch vehicles directly affects the size of instruments, both science user Codes agreed that *precision deployment technology* was crucial to enable high-resolution sensing for future missions. In fact, both have listed it among their top two to five "tall-tent-pole" technologies. Currently, *MADE* is the only funded technology development program within NASA that is developing low-cost solutions to this essential technology.

1.4.2 Will *MADE* Benefit Existing Science Missions?

***MADE* COULD CERTAINLY REDUCE THE COST OF MANY MISSIONS, MIGHT BE NECESSARY FOR SOME STILL ON THE MANIFEST, AND WILL CERTAINLY BE REQUIRED IN THE FUTURE.**

In a recent trade study considering two configurations for the *Global Topographical Mapping Satellite (TOPSAT)* mission, a two-satellite system was selected over a one-satellite system partly because the latter required deployment of a 12-m, millimeter-stable boom. Although a one-satellite system would cost significantly less to launch and operate, the study concluded that such a deployment (without the benefit of *MADE* technology) would cost $45M more for "implementation of state-of-the-art Controls-Structures-Interaction, CSI technology."

Similarly, the *Orbiting Stellar Interferometer (OSI)* mission was recently significantly scaled down in size from an 18-m to a 7-m spacecraft because the original design involved 10 mission-critical deployments of precision optical-metering structure. As a result, the mission has lost much of its resolution and science capability. Despite down-sizing, the mission still involves two mission-critical deployments which mission designers believe will require CSI technology. This however, will still require *MADE* technology to make the deployed structure stable to within the linear tolerance of the active control system.

1.5 *MADE* TECHNOLOGY IS DUAL-USE, ENABLING LARGE NEW COMMERCIAL MARKETS AS WELL AS SIGNIFICANT NASA SCIENCE MISSIONS

Remote Sensing and Global Communications are the two commercial satellite markets currently experiencing the most significant growth. Although many U.S. companies are competing for these markets with existing technologies, *aggressive foreign competition places future U.S. competitiveness and leadership in question.*

For example, as part of its participation in the international Very-Long Baseline Interferometry (VLBI) mission, Japan has developed its MUSES-B spacecraft. The antenna for this spacecraft substantially advances the state-of-the-art of mesh antennas by operating up to 22.5 GHz. With performance better than any similar U.S. instrument, the MUSES-B antenna could find application to many new commercial communication and remote-sensing missions. One can be sure that this is the intention of Nippon Telephone and Telegraph, a principal corporate developer of the MUSES-B antenna.

To ensure continued U.S. leadership in these emerging markets, it is imperative that NASA support the development of "leap-frog" technologies that promise to keep U.S. systems well ahead of foreign competition. To see how *MADE* offers such a technology, we present the following two market impact analyses.

1.5.1 Will *MADE* Benefit Global Communications?

***MADE* IS ESSENTIAL TO PROVIDING LOW-COST HIGH GAIN ANTENNAS FOR SUBMILLIMETER WORLD-WIDE MOBILE COMMUNICATION NETWORKS. THIS WOULD ALLOW US FIRMS TO ENTER FREQUENCY BANDS IN WHICH THERE IS NO FOREIGN COMPETITION.**

In the global communications market, economic competitiveness hinges on the ability to mass-produce, launch, and operate constellations of low-cost spacecraft. Current billion-dollar efforts to develop this market (e.g. Teledesic and Iridium) use relatively low-precision instruments built at low cost using existing and "incremental" technologies. Conversations with technology representatives from the Lockheed-Martin Corp. and the Teledesic Corp. at a recent *MADE* Technical Advisory Group (TAG) meeting indicated the next generation of global communications satellites must incorporate revolutionary technology advancements to enable submillimeter optical frequency, high-bandwidth communications.

For instance, the Teledesic system plans to use the Ka Band (27 to 40 GHz) to support a 500 MHz bandwidth of world-wide internet connections. It has the capacity to support up to 10,000 video conferences simultaneously anywhere on the globe. Their capacity is limited, however, only by the availability of commercial frequencies in this band. This past fall, however, the FCC allocated new frequency bands in the submillimeter (30 GHz-600+ GHz) bands for commercial application. This was due in part to the recent declassification of submillimeter communication equipment by the military. The FCC allocation includes, for example, a 43.5 GHz band with a 3 GHz bandwidth. This high bandwidth tremendously improves data rates, but they are currently accessible only to ground-based mobile equipment. Their use in world-wide networking and communication via satellites is limited by the large transmissivity loss above 30 GHz due primarily to water absorption in the atmosphere. *MADE* technology would break through this barrier by providing a seven-fold increase in receiver sensitivity on orbit. If this happens, it will lead to a *world-wide mobile communications network 10 times the capacity of the planned Teledesic constellation.* There is no competing technology that can exploit this frequency band, foreign or domestic.

1.5.2 Will *MADE* Benefit Remote Sensing Markets?

***MADE* COULD REVOLUTIONIZE COMMERCIAL REMOTE SENSING AND SOLIDIFY U.S. LEADERSHIP IN THIS INDUSTRY.**

Economic competitiveness in the commercial remote sensing market hinges not only on producing low-cost spacecraft, but more importantly, on the ability to deploy high precision instruments from those spacecraft. SVS, Inc. of Albuquerque, New Mexico (an industry partner of*MADE*) is one example of many entrepreneurial ventures blossoming in this new market.

Recently, under an SBIR grant with the Air Force's Phillips Laboratory, physicists at SVS developed an innovative remote imaging system which promises to revolutionize a portion of the remote sensing market. It will provide ultra-high-resolution optical images using a micron-precision deployable aperture reflector. *The only technology that SVS lacked prior to their affiliation with MADE was micron-precision deployable structures.* A Memorandum of Agreement is currently being developed with SVS to adopt *MADE* technology to their system requirements.

1.6 *MADE* INCLUDES AN EFFECTIVE TECHNOLOGY TRANSFER PLAN

In view of the tremendous potential impact to the above missions and commercial markets, the *MADE* team has developed a technology transfer philosophy that directly involves potential end-users in the flight program. This means that corporate partners have been and will continue to be part of the requirements definition, the configuration of the flight experiment, and the comprehension of the data. In fact, technology transfer is a Level 3 component in the *MADE* WBS.

The *MADE* technology transfer plan has two main components: 1) Periodic communication with a Technical Advisory Group (TAG), and 2) Immediate disclosure of technology through non-disclosure agreements. Table 1 shows the *MADE* TAG team members who actively contribute advice to the *MADE* project team. To date, we have negotiated non-disclosure agreements with ABLE, Starsys Research, and SVS.

MADE's proactive approach to technology transfer has already lead to a substantial corporate response. At the time of the submittal of this Phase B proposal, CU has received a request for the CU/PI and the NASA LaRC Co-PI of *MADE* to brief the Vice President of Technical Operations at Lockheed-Martin. This briefing is anticipated for 4/27/95, and it reflects the level of interest and potential impact *MADE* will have on programs with direct economic value. *MADE* truly represents a unique opportunity for NASA to deliver leveraging technology to the aerospace industry.

TABLE 1. *MADE* Technology Transfer is Ensured by Active Participation of Industrial End-Users in the Flight Program Planning. This table lists *MADE* corporate Technical Advisory Group members.

MARTIN MARIETTA	AEC-ABLE ENGINEERING COMPANY, INC.
TRW	SVS INC
STARSYS RESEARCH	Teledesic

1.7 TIMELINESS OF FLIGHT RESULTS

No flight experiment should be flown unless the integration of its technical results will be derived in time to impact the missions to which it applies. The timeliness of the *MADE* results is ensured for several reasons:

- The second phase of New Millennium missions which are the prime driver of the *MADE* technical advances will begin development around the time of flight (mid-1998).
- Commercial applications of *MADE* technology are even more anxious and immediate. Active communication with the *MADE* TAG will ensure rapid assimilation of *MADE* technology and results in these areas.
- Immediately following flight, *MADE* will end the cycle of science mission de-scoping because of the lack of precision deployment technology.

2.0 TECHNICAL DESCRIPTION

This section describes in detail the technical objectives, requirements, and conceptual design of the *MADE* experiment. The intent of this section is to communicate the following qualities:

- *MADE* is the next logical step in space construction technology, and is a significant improvement in the state-of-the-art.
- *MADE* is derived from an extensive history of research at CU, NASA LaRC and Industry.
- Phase A hardware prototypes have demonstrated both feasibility for flight and the potential for a tremendous leap in performance.
- Phase A science testing has provided justification for flight and guidance in choosing specific flight objectives.
- *MADE* has at its core a clearly defined hypothesis which leads to a quantitative flight objective that drives the methodology and the experiment requirements.
- *MADE*'s conceptual design is both feasible and cost-effective, and is based on prototype hardware demonstrated in Phase A.
- *MADE*'s flight measurements and experiment requirements directly and immediately lead to use in future spacecraft.
- *MADE*'s data will be reported in an effective manner that is meaningful for practicing engineers and program managers.
- *MADE* 's project plan has been completely detailed to level 4 for all phases of the flight program.

2.1 EXPERIMENT BACKGROUND

This section defines the relationship of *MADE* to the state-of-the-art, its merit relative to other experiments, and the extensive ground-test and development results which form the basis of the flight configuration and the flight test protocol.

2.1.1 *MADE* is a Fundamental Advancement in the State-of-the-Art of Precision Deployment.

MADE REPRESENTS AT LEAST A 50 FOLD INCREASE IN PRECISION OVER ITS MOST PRECISE DEPLOYABLE COMPETITOR

Every viable flight experiment must be based on a solid understanding of the state-of-the-art and must provide a significant advancement above and beyond the state-of-the-art. For this reason, the Phase A *MADE* effort included an exhaustive study of the technical history of deployable and erectable reflectors. This study encompassed 46 different configurations, 10 of which were flight tested, 20 of which were ground tested, and the remaining 16 were never built. Figure 1 on page 5 compares the size and precision of many of these configurations.

Within this set of reflectors the most precise configurations require human-assisted construction on-orbit. These so-called *erectables* can achieve accuracies approaching that of structures which are ground-assembled using welded, bonded, or bolted joints. The most accurate erectable structure tested to date is the Precision Segmented Reflector (PSR). Developed by LaRC in support of JPL research in advanced instruments for far infrared observatories, this reflector incorporated a metering truss with 150 struts that was fabricated to a precision of about 50 microns RMS. Extensive ground tests of the PSR metering truss disclosed highly linear behavior with load-cycle hysteresis on the order of 5 microns. *Prior to the MADE program, it was generally accepted that mechanical deployable structures would never be as precise as the PSR truss.*

Among deployable technologies, *mesh reflectors* are the most commonly used. Deployed up to 100 meters in diameter, their precision is limited by membrane (anticlastic) curvature and surface roughness, and they are typically only used for frequencies below 5GHz. The most precise mesh antenna design is the Japanese MUSES-B, which uses a pretensioned truss to fight anticlastic distortion to operate at 22 GHz. *Inflatable reflectors* are currently being considered for higher frequency applications because they have smooth surfaces and use inflation pressure to eliminate anticlastic distortion. However, material thermal stability and fabrication tolerances limit their precision to about 1000 microns.

Achieving higher precision requires *solid-surface reflectors* (like the PSR). The highest-precision deployable concept demonstrated to date in ground tests is the TRW HARD (High Accuracy Reflector Development) reflector. Developed under a recently declassified SDIO project, the HARD reflector exhibited approximately 250 microns of deployment repeatability. Although it was designed for active shape compensation to approximately 50-100 microns, this was never actually demonstrated. Unfortunately, in addition to its mechanisms possessing relatively high kinematic imprecision, the HARD reflector is fundamentally limited by the fact that it relies exclusively on the shell stiffness of the deployed reflector segments for dimensional stability.

The two significant advantages of *MADE* technology over the HARD reflector technology are: 1) *MADE* mechanisms achieve *micron-level* passive deployment repeatability and kinematic precision, and 2) *MADE* incorporates a micron-precision metering truss which provides orders-of-magnitude increase in stiffness and enables sub-micron-level active panel positioning.

2.1.2 *MADE* Builds on Extensive Past Research and Leverages Related Current Research

CU, LaRC, and various industry collaborators have been steadily working on deployable structures for over a decade and specifically the problems of precision deployment for over 5 years. *MADE* is built on knowledge gained in these past efforts, and compliments numerous related current research efforts in spacecraft structures and materials. This section reviews this rich pedigree.

DEPLOYABLE STRUCTURES CONCEPTS. During the 1980's, LaRC, Astro Research Corp., TRW, and Lockheed developed concepts for a variety of deployable structures including reflectors. This basic research focused on the simulation of deployment kinematics, prediction of deployment forces, and development of structural concepts that were simple to deploy. Although this research did not develop precision joint mechanisms or deployment actuators, it did identify performance requirements for these devices and stimulated interest in their development.

PRECISION JOINT MECHANISMS. In 1992, CU developed the Batten Actuated Truss (BAT) to study the use of variable-length batten actuators to preload a truss-beam and remove freeplay. Extensive tests of this device identified various sources of nonlinear behavior in preloaded joint mechanisms, as well as gravity-induced destiffening effects. In 1993, complementary to CU's early experimental research in precision deployables, LaRC began studying the structural mechanics and design problem of eliminating joint freeplay and other nonlinearities without applying external preload. Numerous concepts were prototyped and tested, and the results fed directly into the development of the super-linear revolute joint incorporated in the *MADE* flight test article.

PRECISION REFLECTOR PANELS. During the past five years, LaRC has collaborated with Composite Optics, Inc., a leading domestic supplier of precision composite structures, to develop new concepts for light-weight, low-CTE, high-precision graphite-composite reflector panels. *MADE* will leverage this technology investment by employing "off-the-shelf" designs. To reduce costs, the *MADE* flight-test article will incorporate flat-surface panels which are constructed using the same material systems and fabrication techniques as the more-costly doubly-curved panels.

LOW-CTE MATERIALS. Industry's capability to fabricate 10^{-7}/°F-CTE composite struts and reflector panels significantly reduces the potential for thermal control problems on *MADE*-class reflectors. However, substantially less capability exists for achieving ultra-low CTE in machined joint fittings. To fill this technology gap, the Polymeric Materials Branch at LaRC has recently begun developing micro-composites which combine a small amount of polyimide binders with ceramics to produce very-low CTE's (tailorable from ~0 to 8×10^{-6}/°F). These new materials are isotropic, have densities below that of aluminum, can be molded like plastics and machined like aluminum. Thus, they represent not only a substantial advancement in material performance and design flexibility, but also a dramatic reduction in fabrication costs.

PRECISION METROLOGY. Over the past decade, substantial advancements have been made in the field of videometry (video-metrology) including low-cost, high resolution CCD cameras and efficient image processing software. As a consequence, high-precision measurements can now be made without the use of contacting probes (e.g., inductive eddy-current devices), or active laser systems. Thus, it is now becoming practical and relatively inexpensive to integrate precision metrology systems into spacecraft structures. *MADE* takes advantage of these advancements in the design of its instrumentation system.

MULTI-BODY SIMULATION AND ANALYSIS. In the past five years CU researchers have developed breakthroughs in multi-body simulation and analysis techniques. These implicit integration algorithms are over ten times faster than traditional explicit integrators for nonlinear multi-body simulation. Their use in the *MADE* program will enable precise pre-flight simulation of deployment loads and micro-mechanics from component-level dynamic response data. *MADE* researchers at CU have also extended force-state mapping techniques, originally developed at MIT during the 1980's for the MODE experiment, to use in these simulations.

EFFICIENT DEPLOYMENT ACTUATORS. Since precision deployable systems like *MADE* use a large number of deployment actuators, improvements in cost, efficiency, and integration complexity profoundly affect the cost and practicality of the total system. Primarily, the spacecraft industry relies on electric motors or pyrotechnics for deployment actuation. Although quite reliable, electric motors require encoders and controllers which represent added weight and complexity. Pyrotechnics are not precisely controllable and can induce significant shock into the structure.

As one alternative, Starsys Research Corp. (a *MADE* industrial partner) has developed a product line of advanced paraffin-wax actuators that are used on over 85 spacecraft, including over 20 latches on each Iridium satellite. These devices are mechanically simple, and produce high output forces for very low mass and power. As another alternative, the advent of smart materials has enabled a new generation of very-high force/mass actuators that can incorporate innovative and unconventional drive kinematics tailored to the deployment kinematics of the structure. For example, the TRW HARD reflector incorporates panel deployment actuators that articulate through a fairly complex sequence of rotations and translations all driven by a single filament of shape-memory alloy. TRW has loaned this mechanism to CU for evaluation for science testing and engineering evaluation for *MADE*.

PRECISION DYNAMIC SHAPE ADJUSTMENT. Technology from NASA's Control-Structures Interaction (CSI) program enables high-frequency dynamic compensation of micron-level kinematic uncertainties. Although precision dynamic adjustment is not a goal of the *MADE* program, clearly this technology coupled with *MADE*'s micron-precision structures technology could make sub-micron-precision deployable reflectors achievable.

PRECISION QUASI-STATIC SHAPE ADJUSTMENT. As part of the BAT program, CU began studying high-precision, quasi-static adjustment systems by developing a two-stage precision actuator (MicroBAT) that combined a DC-stepper-motor coarse stage with a piezoelectric vernier stage. The concept demonstrated cyclic repeatability of under 200 nanometers over a 0.5 meter cycle range. Building on this experience, researchers at CU collaborated with Starsys Research Corp. during Phase A to develop a concept for a sub-micron-stable combined latching and actuation mechanism ("Latchuator") that holds static positions without using power.

2.1.3 *MADE* Phase A Hardware Prototypes Provide Confidence in Critical Flight Systems

***MADE* PROTOTYPES OF DEPLOYMENT JOINTS AND THE METROLOGY SYSTEM DEMONSTRATE FLIGHT FEASIBILITY, REALISTIC COST, AND THE LIKELIHOOD OF BREAKTHROUGH VALIDATION UPON FLIGHT.**

During Phase A, the *MADE* team made substantial advancements in the state-of-the-art in various component-level technologies. These advancements were demonstrated by hardware prototypes, two of which are presented below.

PRECISION JOINT MECHANISMS. During Phase A, LaRC researchers developed a *super linear revolute (hinge) joint* to eliminate the most common source of nonlinear behavior and kinematic imprecision in deployable structures. The new design (Figure 4) represents a substantial departure from conventional tang and clevis joints in that it incorporates a precision, preloaded angular-contact bearing in place of a simple pin. With only four

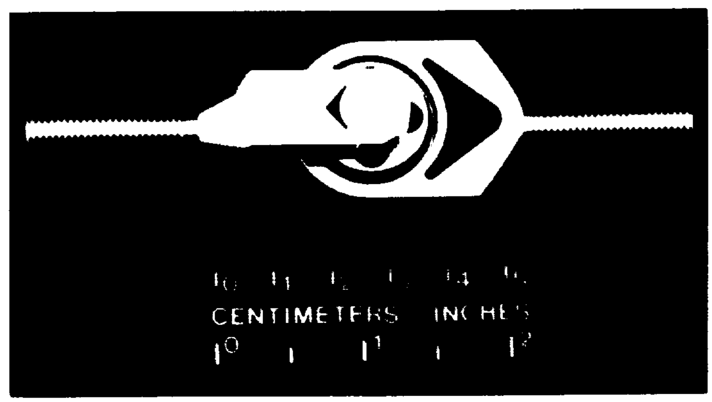

FIGURE 4. The *MADE* precision revolute joint

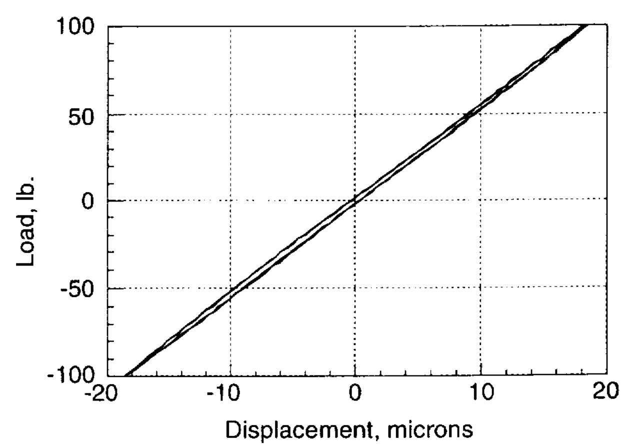

FIGURE 5. The prototype *MADE* joint exhibits one micron of hysteresis over a 100 lb load range.

fairly simple machined parts (not including the bearing, some screws, and an assembly pin), the new design is also relatively cheap and easy to manufacture. A patent disclosure has been filed with the LaRC Patent Council on the innovative new design, and to date, three companies have signed nondisclosure agreements to access patentable information.

The rolling-element bearing produces less than 0.5 in-oz of operating friction and minimal load-cycling hysteresis. The bearing is internally preloaded to eliminate freeplay, and the bearing diameter is maximized to minimize stiffness changes due to nonlinear interface conditions. Finally, the tang and clevis arms have cut outs which divide the load into similar tension and compression load paths to ensure equal tension and compression stiffnesses.

Figure 5 shows the quasi-static load-displacement response measured across the joint during three complete load cycles between 100 lb of tension load and 100 lb of compression load. The joint response is linear to within less than 1 micron of hysteresis. Researchers at LaRC and CU have developed preliminary models of this behavior consistent with the data.

EXTENSIVE TESTS IN PHASE A HAVE DEMONSTRATED THAT MICRON-LEVEL KINEMATIC PRECISION IS ACHIEVABLE IN RELATIVELY LOW-COST REVOLUTE JOINTS.

PRECISION METROLOGY SYSTEM. The most important *MADE* flight instrument will measure the absolute position of the deployed components of the test article. This precision metrology system is a key challenge to flight feasibility. Table 2 compares existing precision metrology system capabilities with *MADE* flight data requirements. The fundamental challenge is to measure absolute precision over a large dynamic range. Interferometric techniques provide large dynamic range, but are only capable of non-interrupted displacement (not position) measurements. *MADE* requires comparative measurements interrupted by successive deployments. Laser-based triangulation sensors are capable of such interrupted measurements, but lack the necessary standoff size. Photogrammetric systems also allow interrupted measurement, but they are not capable of the required level of precision for the given target separation.

TABLE 2. Candidate Metrology Systems

CANDIDATE TECHNOLOGY	PRECISION (μM)	STANDOFF (M)	RANGE (M)	COST
Eddy Current	1	0.01	0.01	low
Interferometric	0.0025	10	10	med.
Laser Triangulation	0.05	0.01	0.01	low
Laser Encoder	0.01	0.5	0.5	med.
Photogrammetry	10 (still) 100 (video)	10	10	high
REQUIREMENT	**<1**	**>3**	**>0.002**	**LOW**

This lack of an adequate "off-the-shelf" system prompted *MADE* researchers develop a new video-based metrology system specifically tailored to the *MADE* requirements.(Figure 5) The system achieves high precision by taking advantage of the fact that target points move only over a range of a few millimeters. This means that high-resolution can be achieved by using a very narrow field of view. As shown in Figure 5, digital images are acquired with a CCD camera and a long distance short range telescope.

As shown in Figure 7, a digital image analysis is used to track the motion of each target between successive images. Sub-pixel resolution is achieved using the two-dimensional cross-correlation field between different acquired images of the same target. As shown in the figure, this cross-correlation field has a distinct peak at the image coordinates corresponding to the target's displacement from one image to the next. Bicubic interpolation of this correlation pattern then yields a peak location accurate to within 1/100 of a pixel.

To obtain the position of the target, the system simultaneously observes the position of a datum point and the target point in the camera's imaging plane. The geometry of the mirror array minimizes the effect of the camera's own motion so that the camera's position and orientation are unimportant to the measurement.

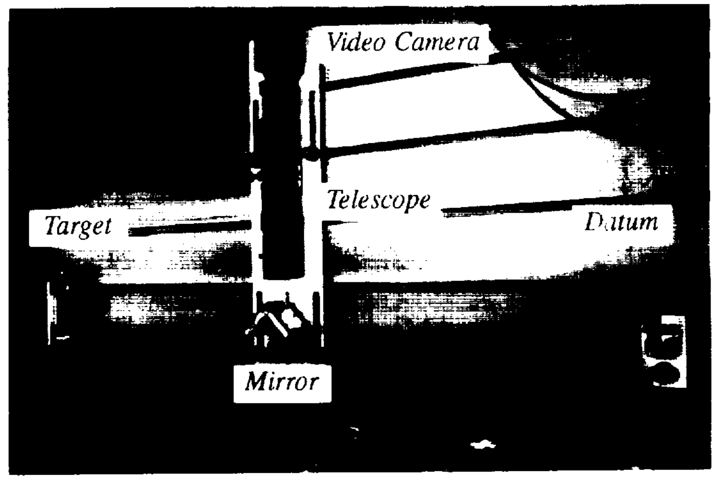

FIGURE 6. The prototype *MADE* metrology system has a 0.3 micron resolution, is constructed of flight-realizable off-the-shelf components, and meets all *MADE* measurement requirements.

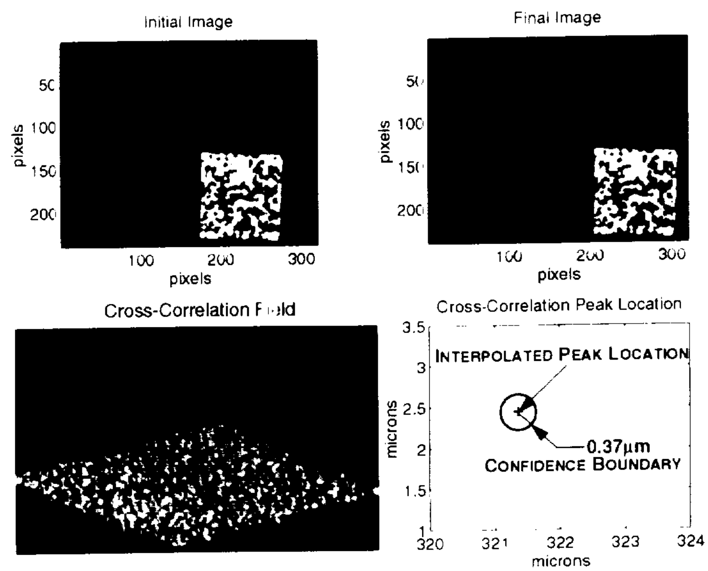

FIGURE 7. Image cross-correlation is used to track the position of target points on the structure. Each target point is a 3mm wide random speckle pattern which maximizes the sharpness of the peak.

The Phase A prototype shown above was constructed for less than $10K using off-the-shelf but space-realizable components. The sensitivity, linearity, and sample standard deviation of the metrology system was assessed using a target mounted on a non-rotating micrometer head. These results indicate that the sample standard deviation is less than 0.4μm and the linear correlation coefficient was over 99%. This means that the flight precision target of 0.1μm can be met by statistically averaging approximately 30 repeated measurements of an individual target position.

INNOVATIVE IMAGING ALGORITHMS COMBINED WITH COMMERCIALLY AVAILABLE DIGITAL VIDEO COMPONENTS HAVE PRODUCED A LOW-COST, ULTRA-HIGH RESOLUTION METROLOGY SYSTEM BETTER AND CHEAPER THAN ANY COMMERCIALLY AVAILABLE SYSTEM.

2.1.4 *MADE* Phase A Hardware Science Tests Provide Justification for Flight and Indicate Critical 0-g Test Objectives

TESTS ON THE MICRON-LEVEL STABILITY OF A PROTOTYPE OF THE *MADE* FLIGHT TEST ARTICLE VALIDATED THE POTENTIAL FOR HIGH PRECISION AND DISCOVERED A CRITICAL NEW PHENOMENON THAT MUST BE EXAMINED IN 0-G.

MICRON-LEVEL NONLINEAR DYNAMICS. Although much of the Phase A hardware development work was done at the component level, many effects can be studied only at the system or subsystem level. During Phase A, *MADE* researchers studied the micron-level nonlinear mechanics of two test articles to develop specific flight test objectives. The first was the LaRC MiniMast structure. This test article is significant because it is typical of the conventional approach to designing precision deployables: freeplay is removed from the joints by external preloading with stiff springs and over-center latches. The second was the *MADE* Science Development Model (SDM), which is a hardware prototype of one wing of the *MADE* deployable metering truss. It uses the internally-preloaded low-friction, precision joints described above.

WHAT IS MICRO-LURCH? Early in Phase A, the *MADE* team performed dynamic tests on two bays of the MiniMast truss-beam in the CU lab. Transient response tests were performed using a laser interferometer to measure the displacements of one joint due to a small impulse applied to another joint. These tests identified a previously undocumented phenomenon called *micro-lurch.*

Data showed that the equilibrium position of a joint shifted 1-20 microns after the structure was subjected to a small impulse. Figure 8 shows a typical transient response measured in these tests. The shift in equilibrium is clear in this plot. It is interesting to note that this *micro-lurch* is in the opposite direction of the applied impulse *and* in the opposite direction of the gravity preload.

MICRO-LURCH IS A CHANGE IN THE EQUILIBRIUM POSITION OF A STRUCTURE FOLLOWING A TRANSIENT DISTURBANCE.

A search of the relevant literature reveals no references to micro-lurch. Apparently, previous testing on deployable structures treated this type of behavior as insignificant. However, such dimensional instabilities are clearly significant for micron-precision mechanical deployables. These observations were confirmed by members of the *MADE* TAG during the 1/27/95 meeting. Although not at all understood, micro-lurching has been observed by spacecraft instrument designers.

IS MICRO-LURCH PREDICTABLE? Multiple repeated tests showed that micro-lurching is probabilistic in direction and magnitude. Furthermore, the distribution of responses appears to be dependant on both the type and magnitude of transient loading.

THE DIRECTION AND MAGNITUDE OF MICRO-LURCH IS A PROBABILISTIC FUNCTION OF THE DISTURBANCE. CURRENTLY IT APPEARS THAT THIS DISTRIBUTION OF RESPONSES MUST BE EXPERIMENTALLY DETERMINED.

WHAT IS A "HAPPY PLACE"? It was also observed during the MiniMast tests that micro-lurches from successive impulses tend to accumulate such that a net displacement was achieved in an asymptotic fashion after 40-50 impulses. Figure 9 shows this trend as exhibited by the MiniMast truss. Once this net displacement is achieved, any successive micro-lurches tend to be relatively low magnitude and randomly directed such that the structure stays

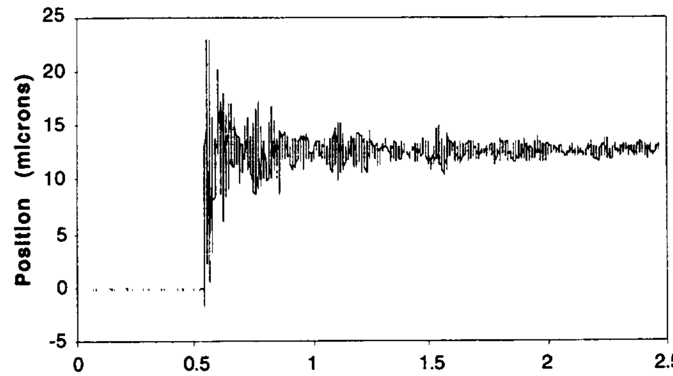

FIGURE 8. Typical Transient Decay and Micro-Lurch of MiniMast

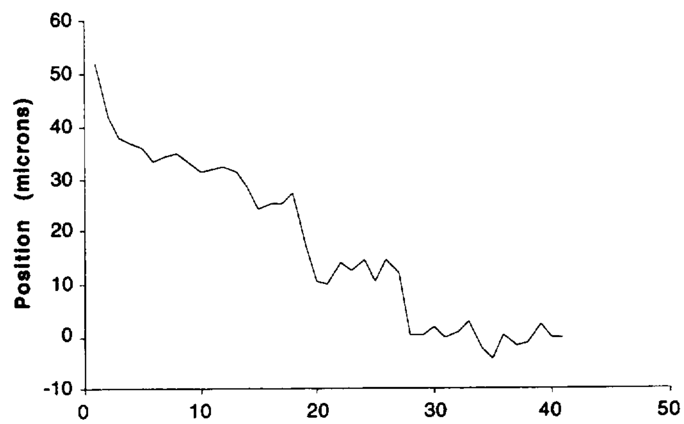

FIGURE 9. MiniMast micro-lurches progressively towards a quasi-stable "Happy Place"

within a small error bound of the position. This quasi-stable position is quite possibly a minimum-energy zone, but the zone itself seems to contain an unpredictable number of possible local minima. It appears to be a static equilibrium zone of possibly fractal dimension, meaning that any two resting places within the zone are just as probable, but are not at all accessible to each other. Because of this complexity, this zone is euphemistically referred to as the structure's **"HAPPY PLACE"**.

A STRUCTURE'S "HAPPY PLACE" IS THE QUASI-STABLE POSITION TOWARDS WHICH THE STRUCTURE TENDS TO MICRO-LURCH AFTER SUCCESSIVE TRANSIENT DISTURBANCES.

MEASUREMENTS OF THE *MADE* SDM'S PRECISION AND STABILITY. Within this context, the *MADE* team conducted similar transient response tests on the *MADE* Science Development Model (SDM) to evaluate its behavior and overall stability (Figure 10). Again, a nanometer resolution laser and the prototype *MADE* metrology system was used to track the motion of a point on the structure under the action of successive impulses.

The results were, to say the least, encouraging. While the SDM exhibits similar types of motion as the MiniMast structure, it is many times more accurate and stable. The typical travel of the tip of the SDM towards its Happy Place (Figure 11 and Figure 12) is 8 to 9 microns with a maximum observed of 18 microns, as opposed to 37 microns and 55 microns for the MiniMast (Figure 9). The SDM's behavior once the Happy Place is reached is stable to

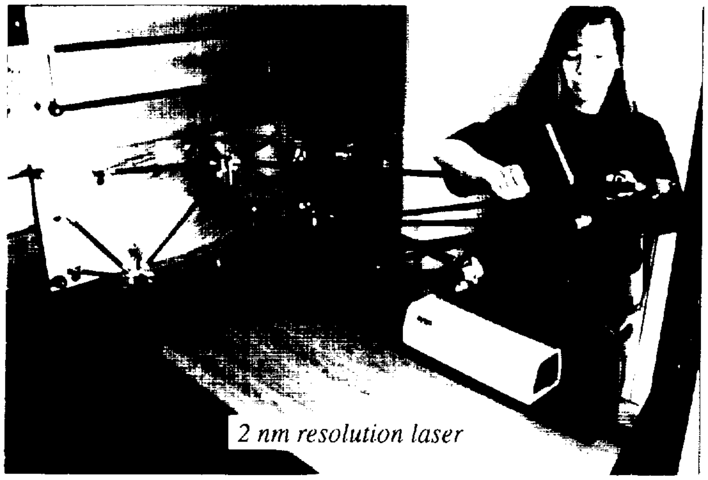

FIGURE 10. Micro-lurch tests on the *MADE* SDM during Phase A have lead to a new theory of the behavior of jointed structures at low motion levels. The pictured undergraduate researcher is applying a calibrated impulse force to excite micro-lurch in the test article.

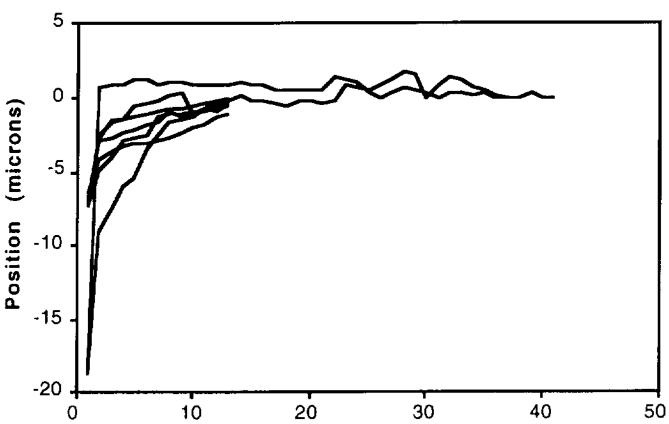

FIGURE 11. The *MADE* SDM micro-lurches much more rapidly to a much more stable "Happy Place" than did MiniMast.

less than 1 micron typically under 50 lb impulsive loads. The 2D data shown in Figure 12 were obtained using the prototype metrology system discussed in Section 2.1.3, so the measured positions between repeated deployments are with respect to a common coordinate system. *This data therefore confirms that the Happy Place is apparently a single zone for this structure and combination of force location and amplitude.*

The key difference between the laboratory environment and the operational environment of NASA spacecraft is the absence of gravity. Since there is no effective way to off-load the gravity pull distributed throughout the SDM structure, the *MADE* SDM test fixture was specifically designed to enable researchers to see the effects of the direction of gravity loading on the behavior of the deployed structure. All testing to date has demonstrated that the micro-motion and responses of the SDM have been permanent micro-lurch motion *against* the direction of the gravity pre-load, and *against* the direction of the applied impulse. Figure 12 shows convincingly that gravity does not seem to noticeably influence the direction of the micro-lurches.

It is hypothesized that the deployment process presses the joints into an initial, unstable position. The impulsive loading and sub-

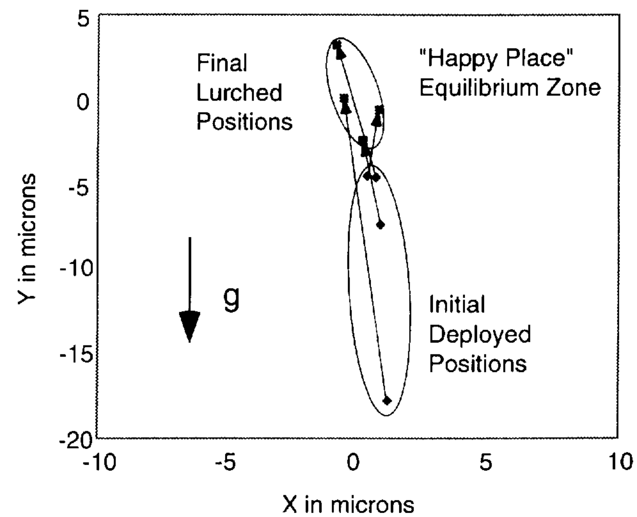

FIGURE 12. Measurements of the position of a single target on the tip of the *MADE* SDM show that the structure's Happy Place is always the same 5 micron wide zone, even after repeated deployments.

sequent vibrational structural response cause the individual joints to seek a more stable, lower energy state. Again, it is hypothesized that the high level of pre-load present in the *MADE* joints, combined with their low friction, dominate the energy states internal to the joints, allowing the joint to seek an equilibrium position that is relatively insensitive to gravity. *This would seem to indicate that the position of the MADE structure is independent of gravity loading thus could be pre-configured on the ground, prior to flight, by adjusting sensor components after buzzing the structure to its Happy Place.*

2.2 METHODOLOGY/OBJECTIVES

The above hypothesis, while logical and supported by ground testing, is insufficient on its own to warrant risking multi-million $ spacecraft. It will not be until the *MADE* structure is flown in a true 0-g environment that the micro-motion of an operational deployable can be adequately predicted and applied to NASA and commercial missions. The *MADE* objectives and procedures described in this section were developed during Phase A on this basis.

2.2.1 Justification for Flight

It is essential that any flight experiment have a traceable and measurable hypothesis which *must* be confirmed by flight experimentation *and* the experimental data must be essential to using the technology in production spacecraft. Within this context, *MADE* will test the following hypothesis derived from the extensive background of research described above:

> **THE ENGINEERING SCIENCE HYPOTHESIS OF *MADE* IS THAT GRAVITY ONLY MODERATELY AFFECTS THE LURCHED EQUILIBRIUM OF THE STRUCTURE AND THEREFORE THE EQUILIBRIUM ZONE ON ORBIT WILL BE WITHIN 1 MICRON OF THE EQUILIBRIUM ZONE ON THE GROUND, ACCOUNTING FOR KNOWN THERMAL AND STATIC DEFORMATIONS. ALSO, THE 5 MICRON WIDTH OF THE ZONE WILL ALSO BE THE SAME IN 0-G.**

More extensively, *MADE* will collect data uniquely available in 0-g to verify, understand, and extend these results to any future application of *MADE* technology. This includes characterizing the results in terms of modal participation factors and force input amplitude and bandwidth, and correlating these results with multi-body nonlinear simulations.

The *MADE* **Justification for Flight** is that this data cannot be derived in 1-g because of perturbations to the mechanics caused by 1-g fixtures and supports, but the data is essential to applying the technology. *Without the flight experiment, the very promising results described in Section 2.1.4 above cannot realize application.*

2.2.2 Experiment Objectives

The broad engineering science objective of *MADE* is to validate the above hypothesis by exhaustive data collection and functional tests from a deployed reflector. The specific objectives necessary to achieve this goal are:

Micro-Lurching to the Happy Place. Verify the hypothesis that discrete points on the deployed configuration migrate under the successive application of impulsive loads to within a zone 5 microns wide. Verify that gravity perturbs this zone by less than 1 micron. Resolve positions to 0.1 microns.

Micro-Mechanics. Characterize how the micron-level migration depends on disturbance force amplitude and location. Measure the dynamics during micro-lurching to determine the participation factors for individual modes.

Linear Mechanics. Measure the linear modal dynamics of the structure in 0-g to correlate with the transient record of individual micro-lurches.

2.2.3 Methodology

To meet these engineering science objectives, *MADE* will execute a series of test protocols designed to quantify the test article's micro-lurching behavior. These protocols will be repeatedly performed to develop a reasonable statistical database for accurate characterization of probabilistic effects. The complete mission test matrix will include substantial pre- and post-flight testing in addition to on-orbit testing so that definitive conclusions can be drawn regarding how micro-lurching depends on gravity and applied force.

Pre-Flight Science Activities. Prior to experiment integration in the Shuttle, the test article joint mechanisms will be tested using precision force-state-mapping and deployment friction will be measured. Component level test data will be used to develop nonlinear multi-body simulations of the deployment mechanics and the micro-mechanical lurching phenomena. The *MADE* flight metrology system will be integrated onto the test article and calibrated using a multi-point (12-DOF) relative position interferometer. Finally, the nominal on-orbit test matrix will be executed with the test article in various gravity orientations.

Flight Science Measurements. The following measurements will be obtained on orbit:

1) Deploy the structure, measuring power and torque required versus time during the deployment.
2) Record the position of the deployed structure at the end of deployment.
3) Apply an impulsive force in one of several locations and directions to induce micro-lurching, measuring the vibration of the structure during each individual micro-lurch.
4) Record the position of the deployed structure and panels at the end of each micro-lurch transient decay.
5) Induce sufficient micro-lurches to find the Happy Place for the test article.
6) Repeat steps one through five sufficiently to obtain a statistical distribution of the Happy Place positions. Note that this means completely stowing, latching, and redeploying the test article between individual tests.
7) Vary impulse location and amplitude and repeat the above procedure.
8) Perform a modal test of the structure to obtain modal vectors, frequencies and damping ratios from the micro-lurch force inputs to the vibration sensor outputs. This data is required for decomposing individual micro-lurch transient free decays into the motion of individual modes.

Flight Test Matrix. Table 3 shows the nominal flight test matrix necessary for complete experiment success. The primary variable is the magnitude of the applied impulses. All forces are scaled with respect to a 1-g determined threshold, A, above which the structure lurches. Two orthogonal inputs are required to examine the effect of out-of-plane and vertical modes on the micro-lurching. The number of repeated impulses is based on 1-g experience with the Phase A SDM. The number of repeated deployments is based on the Phase A observed sample standard deviation and the desire to achieve 5% uncertainty in the measured mean lurch amplitude.

TABLE 3. *MADE* Flight Test Matrix

Variable	Values
Lurching Force Amplitude	0.1A, 0.5A, A, 2A, 5A
Force Input Location/Direction	+X, +Y
Number of Repeated Impulse	40
Number of Repeated Deployments	30

The above procedure will first be executed using the nominal flight test matrix, and data will be downlinked for analysis. If necessary, additional test protocols will be generated and up-linked for execution. The test matrix will be repeated until a statistically significant database has been obtained.

The flight experiment timeline can be estimated as follows. Each deployment, latching, stowage, latching and de-latching cycle lasts 20 minutes, based on the speed of the selected actuators. Each single impulse ringdown requires 5 seconds. With 5 force amplitudes, 2 input locations, 40 impulses and 30 repeated deployments, this is 60,000 seconds of transient data. Adding time for 30 deployment cycles, the total test time is 27 hours. Our requirements add 3 hours margin.

Post-Flight Science Activities. The nominal on-orbit test matrix as well as all up-linked modified protocols will be re-executed with the test article in various gravity orientations. This will bound any effects of pre-launch integration, launch, and landing on the mechanics of the test article. Additional tests will be conducted as needed to resolve unanticipated observations.

How Flight Data Satisfies the Objective. Obtaining the flight data and comparing it with the ground data will directly validate the improved precision of the *MADE* test article over competing technologies. The flight data satisfies the science objectives as follows:

- 0-g micro-lurch data, when compared with 1-g micro-lurch data, will determine whether the Happy Place depends on gravity.
- Measurement of the required torques during deployment will ensure fidelity of the analytical models used to predict the micro-lurch initial condition after deployment.
- Varying force location, bandwidth, and amplitude will characterize the sensitivity of micro-lurching to force parameters and, by comparison with the identical 1-g results, determine if these change in 0-g.
- Modal measurements will allow the decomposition of the micro-lurch transient decays into the participation of individual modes (using established signal processing algorithms).

Indirectly, through successful and repetitive deployment, *MADE* will help to break the current paradigm and guards against the use of mechanical deployables on spacecraft.

2.2.4 Success Criteria

Requirements for Complete Experiment Success. ***MADE*** will be a complete success if all flight protocols are executed and sufficient data is obtained to confirm or invalidate the above hypothesis.

Requirements for Minimum Experiment Success. As a minimum, *MADE* must accomplish at least a single deployment and lurch measurement to verify the position of the asymptotic equilibrium. This will provide partial confidence in application to future spacecraft, but will not include sufficient engineering science to validate the extension of the technology to other structural configurations.

2.3 EXPERIMENT REQUIREMENTS

To ensure traceability and cost controls, a formal set of engineering requirements has been developed for *MADE* in response to the above objectives. An Experiment Requirements Document (ERD) has been written and will be the first document placed under configuration control at the beginning of Phase B. A subset of the requirements developed in the ERD are presented below. The *MADE* team understands the need for a minute level of detail in these requirements, and the complete ERD contains such detail. However, the purpose of this section is to communicate the most important requirements which lead to the development of the conceptual design presented in Section 2.4. All Experiment Requirements are presented below in Table 4.

2.4 EXPERIMENT CONCEPTUAL DESIGN

MADE consists of three major components or subsystems: the carrier, the test article, and the instrumentation (which includes the Experiment Support Module (ESM)). During Phase A, conceptual designs were developed for each of these components based on the engineering requirements presented in the last section. The following subsections explain the conceptual design of these subsystems, their operation and organization.

TABLE 4. ***MADE* Experiment Requirements and Constraints**

1.0	**MISSION/CARRIER**
1.1	**Environment**
1.1.1	Stable thermal environment (minimum DT attitude).
1.1.2	<0.001g background noise (secondary thrusters only)
1.2	**Operations**
1.2.1	Multiple (nominally 30) uninterrupted test windows of approximately 60 minutes each (20 minutes deploy, 40 minutes data)
1.2.2	Approximately 30 hours total test time
1.2.3	Semiautonomous control with crew intervention
1.2.4	On-board data storage
1.2.5	Capability for down-link of data between test protocols
1.2.6	Capability of up-link of new test protocols
2.0	**FLIGHT TEST ARTICLE**
2.0.1	Will be representative of a deployable precision reflector sized to fit within a Taurus class launch vehicle shroud.
2.0.2	Will consist of two deployable reflector panels deployed on top of two deployed metering truss arms.
2.0.3	Will be configured to attach to the top of a Hitchhiker-C MPESS structure with the Shuttle payload bay.
2.0.4	The lowest vibration mode of the testbed in deployed configuration will be at least 10 Hz.
2.0.5	As a goal, the overall structural absolute precision will be 5 microns RMS or less.
2.0.6	As a goal, the overall structural kinematic precision will be 1 microns RMS or less.
2.1	**Reflector Metering Truss**
2.1.1	Will use zero-freeplay rotary joints with less than 5 microns hysteresis over a 100 pound load range and less than 0.5 inch-oz of friction torque.
2.1.2	Net CTE shall be < 10^{-6} / °F
2.1.3	Will be deployable in 1-g in any orientation.
2.2	**Reflector Panels**
2.2.1	Will not be electromagnetically or optically functional, but be mechanically similar to functional panels and have net CTE < 10^{-6}/ °F
2.2.2	As a goal, panel actuators will serve both as launch latch actuators and post-deployment latch actuators.
2.2.3	Following deployment, each panel will be supported in 6 DOF by flexures arranged to reduce the effects of mechanical and thermal distortions.
2.2.4	The panel deployment mechanism must not remain in the load path after deployment.
2.2.5	Passive panel deployment error will be less than 50 microns at each of the 3 attachment locations.
2.2.6	The panel supports on one of the two panels will be adjustable to provide 6 DOF of error compensation over a range of 1 mm.
2.2.7	All panel deployment mechanisms and latches must be reversible for repeated deployment and stowage.
2.2.8	Panel deployment will be accomplished after metering truss deployment.
2.2.9	Panel deployment in 1-g need not be done without the aid of gravity-off-load devices.
2.3	**Latching System**
2.3.1	The testbed components will be latched in its stowed configuration using non-pyrotechnic latches.
2.3.2	The latches must maintain their mechanical integrity during up to 30 pre-flight deployments, up to 30 deployments on-orbit, and up to 30 post-flight deployments.

TABLE 4. *MADE* Experiment Requirements and Constraints

3.0	**INSTRUMENTATION**
3.1	**METROLOGY SYSTEM**
3.1.1	The metrology system will be capable of measuring the vertical and horizontal position coordinates of 6 points on the test article with respect to a single data point on the RCB.
3.1.2	The precision of the metrology system measurements will be 0.1 microns.
3.1.3	The metrology data will be gathered at a rate of up to 10 measurements a second and stored for subsequent ground analysis.
3.1.4	The metrology measurement will be insensitive to the relative position of the instrument and the datum point.
3.2	**JOINT MECHANICS INSTRUMENTATION SYSTEM**
3.2.1	At least one revolute joint will be sufficiently instrumented to measure the transmitted friction torque in the joint and the relative motion during deployment and during micro-lurch testing.
3.3	**VIBRATION INSTRUMENTATION SYSTEM**
3.3.1	Force impulses will be applied independently in two orthogonal locations near the base of the deployed metering truss arms.
3.3.2	Accelerometers will be placed at the base and tip of the metering truss arms to record motion during the micro-lurching transient decays and to obtain modal vectors at the selected locations.
3.4	**ENVIRONMENTAL INSTRUMENTATION SYSTEM**
3.4.1	Six axes of acceleration will be measured at the base of the test article where it interfaces to the MPESS.
3.4.2	The thermal distribution over critical components will be measured and recorded.

2.4.1 Overall Functional Diagram and Subsystem Organization

Figure 13 shows the test article as configured on the MPESS before and after deployment. The stowed and deployed configurations fit within the Shuttle dynamic envelop, but an intermediate panel deployment state (not shown) violates the envelop. For this reason, the test article is connected to the MPESS by three safety release latches under astronaut control via the aft flight deck. Figure 14 shows an exploded view to identify the major systems components.

2.4.2 Carrier

To satisfy the on-orbit environmental and operations requirements stated in Table 4, *MADE* has been configured to fly attached to the top of a Multi-Purpose Experiment Support Structure (MPESS) in the Space Shuttle Payload Bay. No other launch vehicle provides the necessary power, mass, long-term duration experimentation, and post-mission test article return. The Shuttle also provides astronaut interaction via the aft flight deck and periodic air-to-ground data links for reviewing data and modifying protocol selection during the mission. The acceleration data provided by previous SAM measurements indicate that the background acceleration on an MPESS is comparable to the environment in the CU laboratory in which the 1 micron stability measurements and objectives were established. The firing of the secondary thrusters produces an acceleration spike comparable to a person jumping 5 meters from the backstop-mounted SDM experiment.

2.4.3 Test Article

As per Requirements 2.0.1, 2.0.2, and 2.0.3, the *MADE* flight test article is derived from a New Millennium-class science instrument sized to package compactly in a Taurus launch vehicle payload shroud. It incorporates three hexagonal reflector panels that are 1.2 m in diameter and a deployable metering truss that is 0.3 m deep. Packaged, the test article is 1.3 m in diameter and 0.9 m high, while deployed it is 2.4 m in diameter and 0.4 m high.

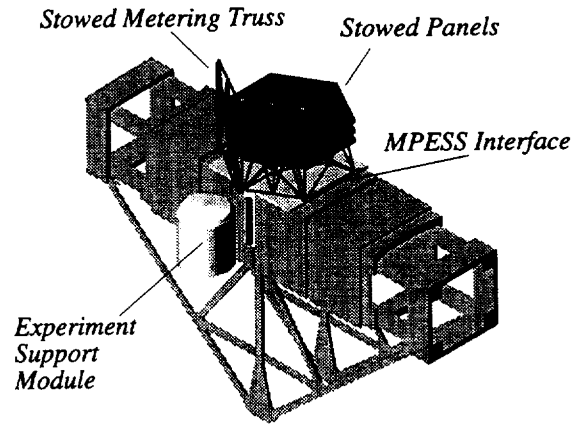

FIGURE 13. *MADE* in stowed configuration atop an MPESS

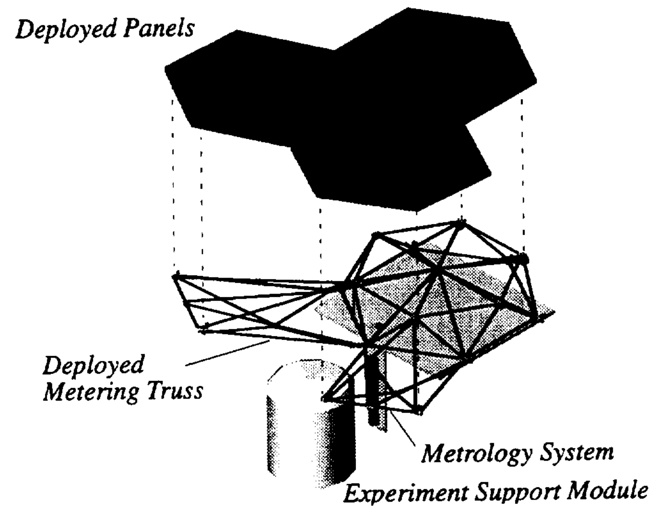

FIGURE 14. *MADE* test article components were designed to follow the Experiment Requirements stated in Section 2.3

To satisfy Requirements 2.0.4, 2.0.5, and 2.0.6, the geometry of the metering truss was evolved from a series of trade studies in which packaged size was minimized while maintaining high packaged and deployed stiffnesses. Hinge and joint locations were determined to simplify deployment kinematics of the truss as well as to accommodate numerous deployment mechanisms that are still being considered for the reflector panels. The metering truss incorporates two adaptations of the zero-freeplay revolute joint discussed previously (Requirement 2.1.1).

To satisfy Requirement 2.1.2, the metering truss struts will be fabricated out of a nearly unidirectional graphite-epoxy or graphite-polyamide composite and the joint fittings will be machined from a ceramic-polyamide. The reflector panels will also be thermally insensitive as per Requirement 2.2.1. If necessary, passive thermal isolation (blanketing or coatings) will be employed on the test article to keep thermal distortions from biasing the data.

The deployment sequence of the test article is as follows: (1) metering truss launch restraints are released (Requirements 2.3.1 and

2.3.2), (2) metering truss wings are deployed (Requirement 2.1.3), and (3) panels are deployed and latched onto flexure supports (Requirements 2.2.7 and 2.2.8). The panels will be deployed, latched, and one of them will be actively positioned with a minimum number of actuators and mechanisms designed to satisfy Requirements 2.2.2 through 2.2.6. To allow the effect of gravity preload to be evaluated in 1-g, the test article will be deployed and tested in various orientations pre- and post- flight (Requirements 2.1.3 and 2.2.9).

2.4.4 Instrumentation

Metrology System. As described above in Section 2.1.3, the metrology system feasibility was perhaps the single most critical design during Phase A. The demonstration of the dual target system gives confidence that Requirements 3.1.1 through 3.1.4 can be satisfied by extending this two-target system to a six target system (Reqt. 3.1.1). Design considerations include placement of the target mirror, calibration of the instrument, and integration into the test article. Figure 15 shows the layout of the metrology system with the panels removed for clarity. The six targets are simultaneously observed from a single camera located on the MPESS just below the test article. A 6-facet mirror orients the ray traces from each target into the field of view of the camera. Independently focusing on individual targets would provide more versatility in the placement of the targets, but this was discarded when it was realized that all 6 targets could be observed with a single telescope. This is possible because the radius of the ray traces from the camera to individual targets are all within the depth of view of the camera. Calibration of the flight metrology system will be done on the ground during science integration using a multi-point interferometer and relative displacement of targets, in a similar manner as done in the Phase A tests.

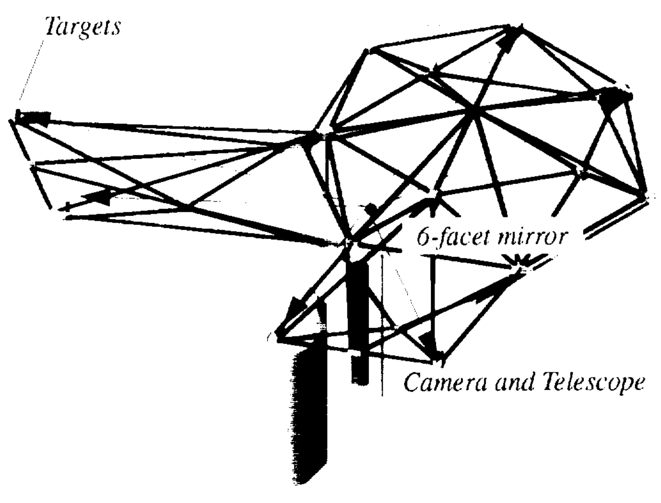

FIGURE 15. Metrology System Conceptual Design

Secondary Instrumentation. To satisfy Requirements 3.2.1 and 3.3.1-3.3.2, two additional measurement subsystems will be included. The first will instrument a single rotary joint to observe the transmitted force (via strain gauges) and the micro-motion (via eddy current sensors). These measurements will be recorded both during deployment and during micro-lurch testing.

Experiment Support Module. The Experiment Support Module (ESM) supplies the commands, conditioning, and power for *MADE*'s sensors and actuators. The trade options ranged from using radiation-hardened and vacuum-tolerant electronics mounted on the test article to keeping the electronics in the middeck or Spacehab. One MPESS mounted ESM using a standard Hitchhiker-S sealed canister was selected because: the electronics are mounted near the test article to reduce manifesting complexity; and the canister enables the internal circulation of an inert gas to eliminate temperature hot-spots. This configuration allows the team to draw up MODE and MACE digital and analog design experience. Figure 16 shows the functions of the ESM. The design maximizes the use of relatively inexpensive off-the-shelf components to service the 25 actuators, 57 real-time analog signals, 1 CCD video signal, 4 mechanisms, 19 latches, and various other housekeeping signals. In addition to the MPESS-provided services listed in Table 5, 22 aft flight deck switches are available for power activation, system reset, and redundant latch control.

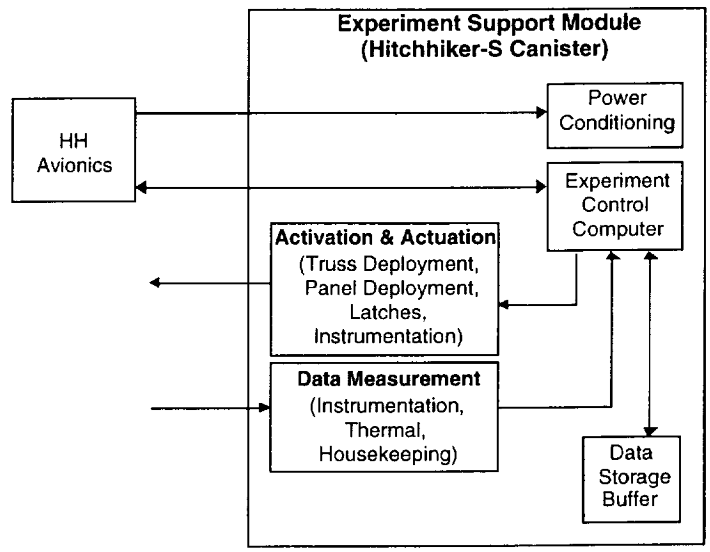

FIGURE 16. ESM Functional Layout

TABLE 5. Carrier Resources and *MADE* Requirements

Resource	MPESS Availability	*MADE* Requirement
Power	1.4 kilowatts	1.0 kilowatt
Attitude Control	Free Drift, +/-1°,+/-0.1°	None
Downlink	Ku-Band, 1.4 Mbaud	1.0 Mbaud
Serial Communications	6 channels, 1.2 Kbaud each	1 channel
Payload Control	6 channels, 24 commands	1 channel, 6 commands

Software. Software allows the test article to function as an integrated experiment. Options included upgrading MACE DSP code, acquiring select modules from other sources, or starting from scratch. Moreover, it was important to decide whether operation of the experiment would entail substantial crew involvement or be controlled largely from the ground. In the end, the availability of the MACE code dictated using the MACE experience to the maximum extent possible. Since Hitchhiker provides high-data rate communications to GSFC, on-orbit control of experiment operations from the ground is easy. Also, a premium was placed on using MACE experience in designing carrier software interfaces.

Sensor and Actuator List The individual sensors and actuators for *MADE* are itemized in Table 6 and Table 7. .

TABLE 6. *MADE* Actuators and Latches

ITEM	FUNCTION	NO.	SOURCE
1	Truss Deployment EM Motor	2	Maxon
2	Reflector Deployment	2	Starsys (p/n HL-9015)
3	Truss Launch Latches	1	Starsys (p/n EP-10025)
4	Truss Deployment Latches	2	
5	Reflector Panel Launch Latches	4	
6	Reflector Panel Deployment Latches	9	
8	Lurch Impulse Actuators	2	PCB Model 086C09

TABLE 7. *MADE* Sensors

ITEM	FUNCTION	NO.	SPECIFICATIONS	SOURCE
1	Truss Deployment Limit Switch			Telemecanique
2	Deployment Torque Sensors	2	DC coupled, 0.1 N-M res.	Sensotec Model QWFK-8M
3	Panel Deployment Limit Switches			Telemecanique
4	Truss Launch Latching Limit Switches			Telemecanique
5	Panel Launch Latch Limit Switches			Telemecanique
6	Latchuator Limit Switches			Telemecanique
7	CCD Camera	1		Cohu Model 4914-2000
8	Frame Grabber Board	1		CORTEX-STD Board
9	Eddy Current Sensors	3	20 nm res.	Bentley-Nevada
10	Strain Gauges	24		Measurements Group
11	Accelerometers	18	500 Hz BW, AC coupled, 25 g	PCB Model 356A08
11	Input force load cell	3	500 Hz BW, DC coupled, 100 lb	PCB Model 208A02
12	Thermocouples	3		Minco Products
13	Low g accelerometers	6	Not required if flown with SAMS module	Allied Signal Model QA-3000-010

2.4.5 Maturity of the Conceptual Design

The *MADE* conceptual design has matured considerably during Phase A because of the development of prototype hardware for the critical components. The most critical item in this regard was the flight metrology system, and Phase A ground tests have proven its feasibility. The *MADE* team believes the conceptual design is sufficiently mature to undergo a Phase B combined Requirements Review/Conceptual Design Review within the first five months after contract. This maturity is reflected in the technical risks and programmatic risks listed below.

REMAINING TECHNICAL RISKS. A mature flight experiment at the end of Phase A will have no remaining technical risks which determine feasibility of the experiment. *MADE*'s remaining risks are all engineering level implementation specifics, and in each case we have developed alternative backup technologies with less performance but also less risk.

TABLE 8. Primary and Backup Technologies Mitigate the Major *MADE* Technical Risks

COMPONENT	PRIMARY	STATUS	BACKUP
Actuators and Latches	Paraffin actuators	Flight proven	Brushless DC motors
Metrology System	CCD Camera	Phase A demonstration	Photogrammetry
Panel Deployment	LaRC Screw-Jack	Phase A demonstration	CU Four-Bar rotary joint of TRW HARD mechanism

REMAINING PROGRAMMATIC RISKS. We have identified no remaining programmatic risks for *MADE*.

SUMMARY OF *MADE* DESIGN TRADES AND DOWN-SIZING DECISIONS. Due in part to our response to the Phase A reviewers comments, we considered an extensive number of *MADE* down-sizing options. Each discarded option is listed and explained in Table 9.

TABLE 9. Discarded *MADE* Down-Sizing Options

Deploy no panels
• Post-deployment mating of two deployed articles (metering truss and panel) is a critical capability required by science customers
Deploy only one wing
• Side-by-side deployment of two wings validates lateral precision of the deployment.
Use non-realistic structure
• Credibility of science customers hinges on flight demonstration of realistic hardware.
Use scale-model structure
• Credibility of science customers • Nonlinear micro-lurching is difficult to scale because it depends on bearing machine tolerances.
Use non-reversible latches
• A single deployment would mean the test article could not be recovered and post-flight 1-g test bounds would not be performed. • A single deployment would also provide no data on the random distribution of the initially deployed configuration.
Remove latchuators
• Precision adjustment of flight qualified mechanisms is of direct interest to Starsys Research, a prime industrial partner in *MADE*. Starsys is absorbing engineering development costs for this requirement. • For the latchuator to be feasible, its micro-mechanics must be compatible with the low level of kinematic imprecision in the rotary joints.

2.4.6 Safety and Hazard Control

MADE has been designed to minimize the impact of safety hazards on overall cost. Perceived hazards currently mitigated by provisions in the *MADE* design include: incomplete deployment/inability to re-stow, electrical shock, ignition of flammable materials, sharp edges, electromagnetic interference from *MADE* subsystems, materials outgassing in vacuum environment, structural failure, and over-temperature operation of equipment. The first hazard listed, incomplete deployment/inability to restore, is considered the most important. It is controlled by using oversized actuators, and by incorporating emergency release latches under crew control via switches on the aft flight deck. All other hazards are not deemed extraordinary; they are mitigated using the standard control approaches developed by PSI during the MODE and MACE experiments. The extensive experience of the project team as a whole and PSI in particular, will ensure any additional hazards are identified and accommodated early in Phase B.

2.4.7 Risk Management

Development Risk Management. In addition to risk minimization methods applied in project management and experiment integration tasks, the risks specifically associated with flight hardware development are controlled through a series of steps spanning the entire project schedule. First, the engineering model will be used to identify potential problems before flight hardware design has finished. This will allow early identification of any design flaws and potential solutions as well as long-lead procurement items necessary for flight hardware fabrication. Thus redesign and procurement delays will be held to a minimum. Second, some engineering model testing will be completed prior to the Hardware Critical Design Review, so that engineering model performance data will be available before the detailed design of the flight hardware is finalized. Third, the hardware design will be placed under configuration control immediately following CDR. Subsequent changes to the design will be subject to guidelines in the *MADE* document change policy. Fourth, after fabrication is completed, the hardware will undergo acceptance tests, as well as all certification tests required to comply with SSP interface requirements and safety policy. In combination with the extensive spaceflight experience of the project team, the procedures described in this section will serve to minimize development risks and ensure successful achievement of *MADE* objectives.

Configuration Management. Configuration management is an integral part of producing high quality products and services which fulfill customer requirements. It comprises three activities: identification, control, and status tracking. PSI will develop a *MADE* Configuration Management Plan describing the implementation of: Requirements; Design; Acceptance Criteria Specification Documents; Development, Certification, and Integration Plan; Experiment Document; Configuration Identification Record (containing a definitive listing of all controlled items and their level of control); Document/Drawing/ Schematic, Hardware, Software, and Change Control (all tracked in respective logs); and Configuration Status Tracking (central log containing records of all change requests and their dispositions). These are the same tools successfully employed in all of PSI's spaceflight projects, and they serve to minimize nonconformance incidents.

Quality. The *MADE* team will deliver *MADE* hardware, software, and services in accordance with *MADE* project quality assurance/control procedures that will be described in the *MADE* Quality Program Plan. The project Quality Engineer will ensure that quality concerns (including safety, reliability, maintainability, testability, producibility, supportability, and human engineering) are addressed in every aspect of the project, including project management, hardware design, procurement and fabrication, subsystem and integrated system testing, packing and shipping, and final flight readiness preparation. The Quality Engineer will report directly to the PI/PM at CU. The Quality Plan will be compatible with a Class-D modified payload. It will emphasize prevention of nonconformances through total adherence to documented project requirements and will provide a comprehensive approach to detecting, documenting, and resolving nonconformances, with emphasis on preventing their recurrence. In support of the Plan, PSI will implement Inventory, Procurement, Fabrication, Non-Conformance, and Test and Evaluation Controls, to ensure that all articles and materials procured and produced meet *MADE* project requirements.

2.5 REPORTING PLAN

The *MADE* team is anxious to have their results widely disseminated throughout the spacecraft design community as well as the academic community. First, regular meetings with our TAG team will ensure periodic direct review of the experiment requirements and progress to date. Second, papers will be presented at technical conferences and submitted to archival journals describing the experiment and its results. Third, recognizing that printed papers and reports constitute only a small part of technology transfer, the *MADE* team will seek out individuals within our TAG team industrial partners who will spend a period of time one-on-one working with *MADE* researchers at CU. Last, the final report will be presented to NASA after flight reviewing in detail all flight data and results.

3.0 WORK BREAKDOWN STRUCTURE

Figure 17 provides a block diagram of the *MADE* Work Breakdown Structure (WBS). Per the Submission Requirements, only Levels 1 through 3 are presented. For the purposes of schedule and budgeting, however, the internal WBS has been taken in most cases to Level 4 and even Level 5 detail for not only Phase B but also Phase C/D.

4.0 SCHEDULE PLANNING

Figure 19 provides the Attachment A schedule for Phase B and Figure 19 provides the Attachment A schedule for Phase C/D. Each figure shows Program Reviews, Integration Milestones, and Management Events, as well as a complete schedule of WBS items. Phase B extends from 7/95 through 4/96, and ends with the PDR and NAR. Phase C/D extends from 5/96 through 12/98. CDR occurs at the end of FY 96, and Launch is in 7/98. This ambitious schedule is the tightest reasonable for integration of a payload in the Shuttle Payload Bay. Strict adherence to this schedule, coordinated by the PI/PM, the Co-PI, and the PSI/PM will minimize deviations. We have verbally verified lead time for the most critical schedule items. Note that Program Management functions are spread throughout all Phases, and so are not listed in the schedule.

4.1 TASK DESCRIPTIONS

Project Management (1.0) includes all tasks related to coordinating, tracking, and controlling*MADE* progress. Project Planning (1.1) includes schedule development and maintenance, implementation planning, project staffing, and meetings. Financial Management and Reporting (1.2) includes budget tracking (1.2.1), reporting (1.2.2), and subcontract monitoring (1.2.3). Task Management (1.3) includes period monitoring of task progress an anticipation of programmatic impacts with sufficient notice to mitigate any cost growth or schedule delay. Customer Interface (1.4) encompasses all interaction with the NASA program monitor and status reporting. LaRC Management is included in 1.5 and PSI Management is included in 1.6. Quality (1.7) includes development of a quality program plan and nonconformance tracking.

System Engineering (2.0) includes tasks which permeate all

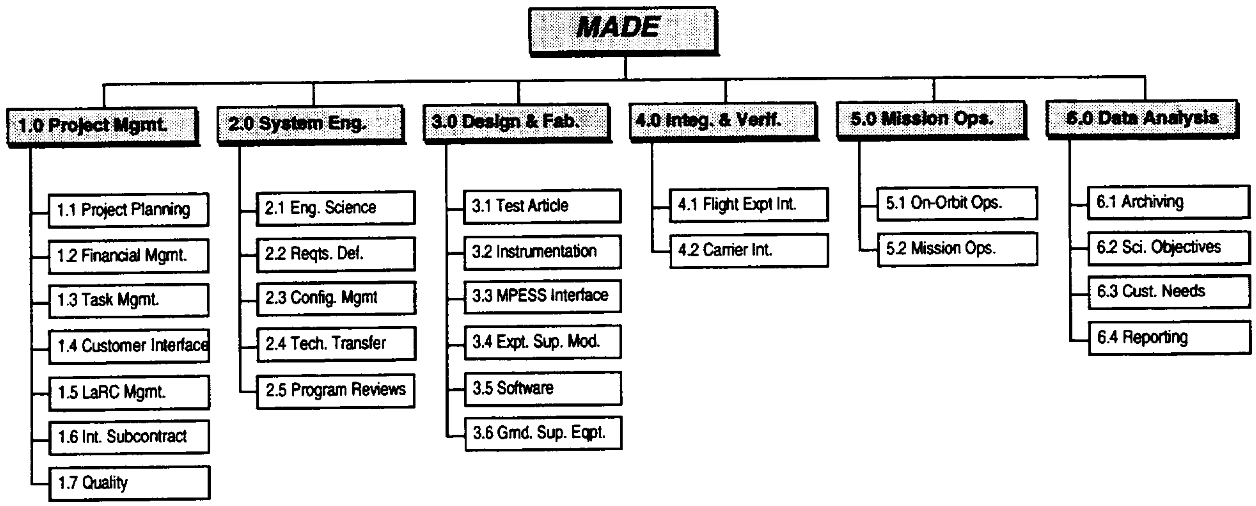

FIGURE 17. *MADE*'s Work Breakdown Structure

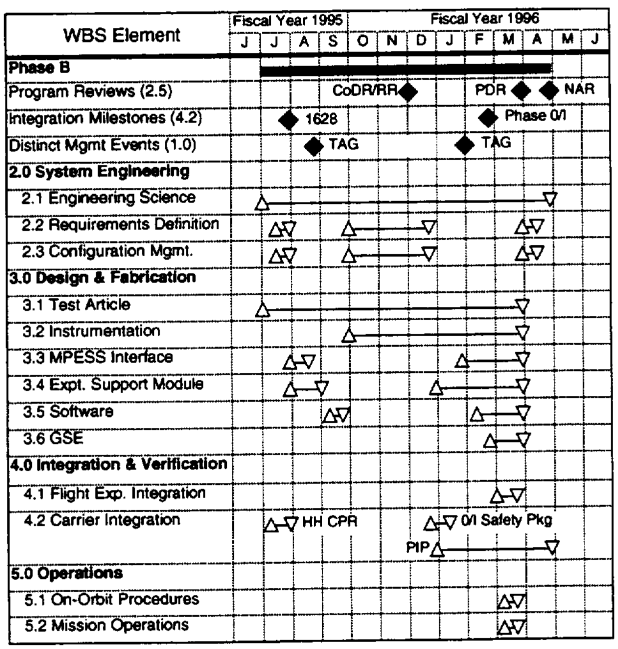

FIGURE 18. Schedule for *MADE* Phase B. Note that Project Management spans the duration of the project and is not shown.

aspects of the program: engineering science, requirements definition, configuration management, commercialization & technology transfer, and program review. Engineering Science (2.1) involves engineering and measurement science tasks such as detailed theoretical modeling and analysis of the test article design, development of test protocols, and performance evaluation. These tasks allow us to continuously track the ability of the system to achieve the program objectives. Requirements Definition (2.2) includes revision of the ERD (2.2.1) developed in Phase A, and its flow down to the requirements levied on the MADE subsystems in 2.2.2 through 2.2.4. Constraints such as power, volume, mass, downlink, etc. are quantified in 2.3.4, and drive the design tasks in 3. The requirements are frozen in Phase B at the Requirements Review. System conceptual development occurred in Phase A; design refinement is a Phase B task, and maintenance occurs in Phase C/D. Configuration Management (2.3) ensures that delivered subsystems meet their design requirements, resource allocation, and interface requirements. Technology Transfer (2.4)

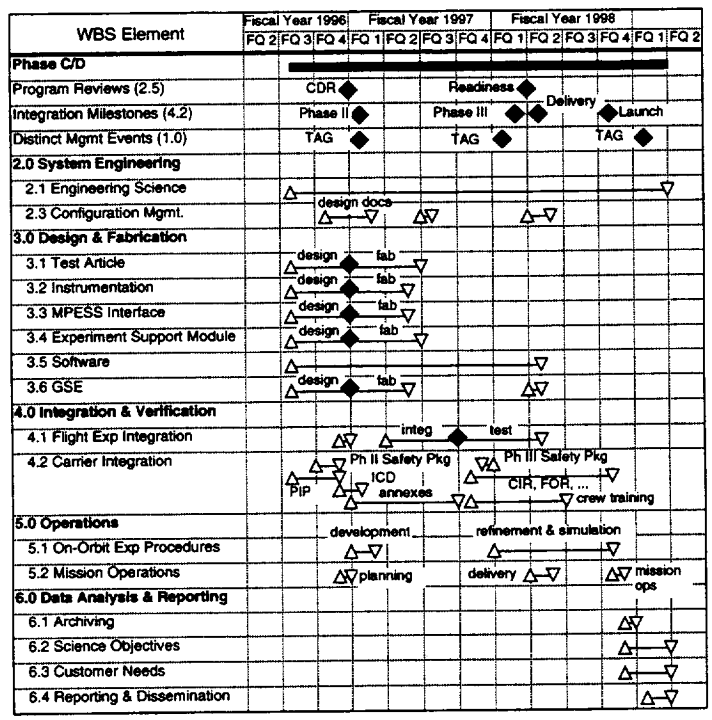

FIGURE 19. Schedule for *MADE* Phase C/D.

includes all interaction with potential end-users, including TAG meetings. Program Reviews (2.5) encompasses preparation for and support of all major reviews.

DESIGN AND FABRICATION (3.0) comprises the design, fabrication, and procurement of all of the MADE subsystems. Notice that Software (3.5) and Ground Support Equipment (3.6) are high level tasks because of their importance to real-time flight operations. Phase B involves the finalization of the conceptual design and conduct of the preliminary design. Phase C/D involves the conduct of the final design and the fabrication and procurement of the flight hardware and support systems.

INTEGRATION & VERIFICATION (4.0) comprises flight experiment integration and carrier integration. Flight Experiment Integration (4.1) includes all activities related to the assembly of the MADE subsystems into an integrated flight experiment such as subsystem integration, system functional checks, system characterization, and environmental testing. Carrier Integration (4.2) includes all activities related to the integration of the flight experiment from 4.1 onto a Shuttle mission such as integration reviews, payload safety reviews, required shuttle payload documentation, associated verification activities, and crew training. Most of these tasks occur in Phase C/D with the exception of preliminary integration and test planning (4.1.1, 4.1.2), Form 1628 & Hitchhiker Customer Payload Requirements (CPR) Submittals (4.2.1), and the Phase 0/I Safety Review. Form 1628 provides NASA HQ's authorization to initiate contact with the Shuttle integration organizations at JSC and GSFC (MPESS Hitchhiker). It is imperative that this submittal occur at the beginning of Phase B since all carrier integration tasks start at this point and drive the duration of the program. The CPR document is the governing document for all Hitchhiker payloads; it lists design, interface, test, and operation requirements for all subsystems. An initial version will be completed during Phase B and modified in subsequent phases as the design matures. The Phase 0/I Safety Review is the first step in carrier integration and identifies the safety critical systems as well as plans for their resolution supplied to the carrier's safety office.

OPERATIONS (5.0) are primarily Phase C/D activities defining how the experiment will be operated on-orbit (5.1) and from the ground through the MADE POCC at GSFC (5.2). Development of on-orbit procedures occurs concurrently with the flight experiment integration (4.1).

DATA ANALYSIS AND REPORTING (6.0) primarily includes all post-flight analyses and presentation of *MADE* results. Archiving (6.1) includes data logging on a World-Wide-Web server and maintenance of project reports on this network. Data analysis is divided into Science Objectives Analysis (6.2) and Customer Needs Analysis (6.3), which specifically interprets *MADE* flight results in the context of given customer group applications. Reporting (6.4) includes all functions described in Section 2.5 on page 20.

5.0 MANAGEMENT PLAN

5.1 PROJECT ORGANIZATION AND MANAGEMENT APPROACH

The *MADE* team has been assembled to ensure experimental success, to minimize development risks, and to guarantee compliance with all the appropriate NASA Space Shuttle Program (SSP) safety, integration, and certification requirements. This team stands ready to successfully complete the *MADE* project on time, on budget, and with the highest possible scientific standards. CU provides technical and scientific leadership to the team, as well as the financial and administrative management. LaRC shares technical and scientific responsibility, and will also manage design and fabrication of the flight test article. The primary subcontractor, Payload Systems Inc. (PSI), is a minority-owned small business with an extensive background in manned spaceflight experiments. PSI will fabricate the instrumentation hardware for *MADE* as proposed herein, and will be responsible for all experiment integration tasks.

Responsibilities for the *MADE* project are divided into three major categories: *project management*; *experiment development and analysis*; and *flight systems and integration*. Project Management is divided into management and fiscal control. Quality, though or-

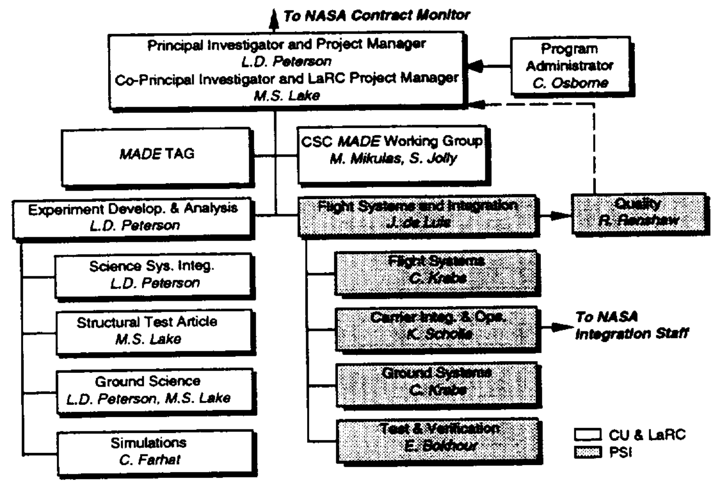

FIGURE 20. The *MADE* organization is a streamlined, focused subset of the originally proposed team.

ganizationally part of Flight Systems and Integration, retains the ability to report directly to the *MADE* PI, thereby providing independent quality control oversight. Also shown on the figure are interfaces with NASA project management and integration staff.

PROJECT MANAGEMENT includes fiscal management, sub-contractor oversight, administration, performance assurance, and configuration control. Activities include financial reporting, contract negotiation, and certification of acceptance procedures. This task is the primary responsibility of CU, and under the direct responsibility of the PI/Project Manager. He is assisted by the Program Administrator.

EXPERIMENT DEVELOPMENT AND ANALYSIS encompasses all *MADE* research activities both in the laboratory and in space. These activities include ground studies, engineering model development, flight procedures development, science operations during the flight, and postflight data analysis and reporting. These activities will be both managed and performed within CU under the direction of the PI. He is assisted by CU support staff and faculty, as well as graduate and undergraduate students.

FLIGHT SYSTEMS AND INTEGRATION include all activities necessary to transform the laboratory-based experiment into a fully space-qualified Space Shuttle payload. These include fabrication and testing of all hardware, and development of appropriate control software. Also included are the integration tasks: schedule, negotiation, and reviews leading to the allocation of shuttle resources (weight, volume, power, crew time, ground processing, and flight operations) as well as successful compliance with shuttle safety and certification requirements. These activities are the responsibility of the Hardware Development Engineer and the Integration Engineer, assisted by other members of the PSI engineering and technical staff, and under the direction of the PSI Project Manager.

5.2 KEY PERSONNEL AND RESPONSIBILITIES

The project team brings to *MADE* broad-based and substantial experience in manned and unmanned spaceflight. The *MADE* team realizes the importance of a complete but streamlined management structure in the successful performance of flight experiments. The entire team is already in place and the members are prepared to assume their functions as the project transitions to Phase B. This serves to minimize transition time and development risk, while maximizing the expected scientific return.

PRINCIPAL INVESTIGATOR/PROGRAM MANAGER. The Principal Investigator/Program Manager for *MADE* is Prof. Lee D. Peterson. Dr. Peterson is an internationally recognized expert in experimental methodologies for spacecraft structures, including ground test methodology development, precision reconfigurable structures technology, and experimental vibration test methods. He has a long association with successful flight experiment programs. He was the Deputy Program Manager under Prof. Edward F. Crawley at MIT for the successful MODE In-STEP experiment during its Phase A development. He designed, developed and implemented the KC-135 flight experiments which were the precursor to the MODE flight experiment, and was responsible for the Phase B/C/D planning for MODE. Later, he served on the MODE TAG and was part of the ground operations team at NASA Johnson Spaceflight Center (JSC) during the MODE flight on STS-48 in September 1991. Before jointing the faculty at CU in August of 1991, he was Principal Scientist on a successful experimental technology development program at Sandia National Laboratories, where he had programmatic responsibilities similar to those on *MADE*. At CU, he has lead the development of the Structural Dynamics and Controls Laboratory (SDCL), where much of the *MADE* pre-flight science testing will be done. His research program at CU was the first to document the micro-lurch phenomenon that is the central scientific issue to be resolved by *MADE*. He is assisted by CU Graduate Students, Undergraduate Students, Faculty, and Staff.

CO-PRINCIPAL INVESTIGATOR. The Co-Principal Investigator for *MADE* is Dr. Mark S. Lake. Dr. Lake has more than 10 years of experience in research and development of advanced spacecraft structures. He is recognized as an authority on the mechanics of truss structures and joint mechanisms and has contributed to the design of numerous ground and flight test articles including various components for NASA's Precision Segmented Reflector program. Dr. Lake was Project Manager and Technical Advisor for the Joint Damping Experiment (JDX), and as such oversaw all technical and contractual aspects for JDX. Dr. Lake has also contributed extensively to the design and validation of hardware and procedures for EVA assembly of structures. During Phase A, he lead the LaRC development of the *MADE* prototype hardware, including the development of the superlinear revolute joint that is a central technological contribution of *MADE*.

As **PSI PROJECT MANAGER**, Dr. Javier de Luis will direct the Flight Systems and Integration effort. Ms. Kimberly Scholle will be responsible for experiment integration and flight hardware certification testing. She will additionally serve as the primary interface between the *MADE* payload and the SSP integration process. These two team members served in similar roles for previous IN-STEP experiments, including the MODE and MACE projects. Flight hardware development is the responsibility of Mr. Christopher Krebs, PE. Mr. Krebs served as senior mechanical engineer on the MODE and MACE projects. Before joining PSI, he designed and integrated several Shuttle payload bay experiments as well as sounding rocket interferometric payloads for the USAF. These three primary team members will be assisted by the PSI engineering staff, all of whom are experienced in designing and flying scientific payloads in space on several different carriers, including Shuttle, Spacelab, and the Russian *Mir* space station.

MADE will be assisted by several faculty at CU. The CSC *MADE* Working Group includes Prof. Martin M. Mikulas, Jr. and Prof. Steve Jolly. Before joining the faculty at CU in December 1990, Dr. Mikulas served 30 years at NASA LaRC, where he was Head of the Structural Concepts Branch. His primary responsibility is internal CSC review of program technical objectives for *MADE*. Dr. Jolly will apply his expertise in mission analysis to ensure *MADE* remains relevant to customer needs throughout the program. All *MADE* numerical simulations will be conducted by Prof. Charbel Farhat, who is an internationally recognized expert in multibody nonlinear simulations and parallel computing.

5.3 CAPABILITIES, FLIGHT AND RELATED EXPERIENCE

The **UNIVERSITY OF COLORADO CENTER FOR SPACE CONSTRUCTION** (CU/CSC) was formed in 1988 by NASA to serve as a Space Engineering Research Center for excellence in space construction technology. The Structural Dynamics and Control Laboratory (SDCL) was founded in 1991 when Dr. Peterson joined the faculty at CSC.(See Figure 21) This facility represents a nearly $1M investment by sponsored research, donations, and the state of Colorado. It includes a large high bay (roughly the size of the Shuttle payload bay) in which the Phase C preflight and the Phase D/E post-flight science activities will occur.

FIGURE 21. The CU/SDCL is a premier facility illustrating the positive impact of NASA-sponsored research on the next generation of engineers. All projects, including *MADE*, involve undergraduates.

The **NASA LARC STRUCTURAL MECHANICS BRANCH (SMB)** has been an international leader in the development of fundamental and applied techniques for the design, analysis, and testing of aircraft and spacecraft structures since its inception over 50 years ago. SMB personnel have substantial experience in nonlinear structural mechanics, advanced structural concept, and composite airframe and spacecraft design. They have also been responsible for developing hardware and procedures for two major structural assembly flight experiments: ACCESS and ASEM. The Structures and Materials Research Laboratory at LaRC includes numerous component testing machines and unique structural test cells and fixtures for a wide variety of structural tests.

PAYLOAD SYSTEMS INC. is a minority-owned small business based in Massachusetts. Founded in 1984 to provide science and engineering services for spaceflight experiments, PSI has an outstanding history of supporting US. and foreign investigators in moving from ground-based to space-based research. PSI was selected as the primary subcontractor because of their excellent performance on MODE, as well as related experience on other manned spaceflight experiments, including STS-9 and Atlas-1 (for which PSI provided a Payload Specialist), the STS-51D Ocular Counter-rolling Experiment, the STS-61A (D-1) Vestibular Schlitten Experiment, the IML-1 Mental Workload and Vestibular Investigations Experiments, and MACE.

5.4 INSTITUTIONAL SUPPORT

5.4.1 Organizational Commitment

The *MADE* project is of vital importance to CU/CSC as the most important component of the continuation of the Center's research thrusts begun nearly seven years ago. The *MADE* team has received commitments of office space and resource allocations from the University to support the flight program.

In addition to its important and primary impact on research, *MADE* will provide an educational focus as well as unparalleled motivation and experience for undergraduate and graduate engineering students. It will provide direct motivation and examples for approximately seven graduate students over its project lifetime, but its impact will reach much beyond the core group involved in *MADE*. The potential impact of *MADE* on education is well-recognized by the PI, who himself was personally motivated by the EASE/ACCESS and the MODE flight experiments during his undergraduate/graduate years at MIT. In fact, *MADE* will play a central role in motivating students throughout the College of Engineering in its new, $15M Integrated Teaching and Learning Laboratory, scheduled to open in January 1997. Prof. Peterson serves as Technical Director of this premier educational facility as part of his teaching duties at the University.

LaRC has historically played a leading role in NASA's structures technology development program. Because of its basic science investigation into uncertain, nonlinear mechanics, *MADE* will be a complementary part of LaRC's overall program, including not only aerospace but also aeronautical structures research. Dr. James H. Starnes, Jr. the Head of LaRC's Structural Mechanics Branch recognizes not only the basic research value of *MADE*, but also the substantial NASA and commercial mission potential it represents. With this in mind, he has committed to fully support the program throughout its duration. LaRC's Spaceflight Experiment Initiatives Review Committee (SEIRC) has reviewed *MADE* and unanimously endorsed it to LaRC senior management as being well conceived and technically consistent with Center goals. Finally, Technology Thrust Leaders in LaRC's Space and Atmospheric Sciences Planning Group view *MADE* as a significant and enabling part of LaRC's contribution to NASA's New Millennium Initiative. Scientists in the LaRC Atmospheric Sciences Division have endorsed *MADE* and have begun developing advanced instrumentation concepts which use *MADE* technology to reduce future mission costs.

At Payload Systems, Dr. de Luis will act as the PSI *MADE* Project Manager. As president of PSI, his participation on the *MADE* team will provide the highest level of corporate support and commitment to this project.

5.4.2 Facilities and Equipment

Payload Systems has a 10,000 class clean-room facility dedicated to assembly and testing of space flight hardware. Directly adjacent to the spaceflight hardware assembly room is an electronics and non-flight hardware assembly and checkout laboratory. PSI also has two CAD facilities dedicated to spaceflight hardware design tasks. Locked, limited access archive facilities are available for controlled drawings and documents. All items procured for flight hardware fabrication are tracked on a software platform developed specifically for that purpose by PSI. Other facilities of interest include a configuration-controlled software development suite on dedicated PCs.

Vibration, thermal/vacuum testing will be conducted at NASA LaRC. EMI and off-gas testing will be conducted at JSC facilities.

The SDCL at CU provides complete equipment for pre-flight and post-flight science integration. Minor fixturing and accommodation modifications to the SDCL High Bay will be implemented in Phase C/D to accommodate the flight article during science integration testing.

5.5 MANAGEMENT FUNCTIONS

This section outlines the policies and procedures that will be used to ensure successful project completion without placing unreasonable burdens on the project budget and resources.

5.5.1 Science Development Management

CU will ensure successful achievement of the *MADE* scientific goals by verifying that all engineering science requirements are met. This will be accomplished in three stages. First, the formal Experiment Requirements Document (ERD) draft in Phase A will be brought up to date at the beginning of Phase B and placed under configuration control. All subsequent technical requirements and designs will be derived from it. Second, the PSI team will participate during the fabrication of the *MADE* prototype, providing design guidance with regards to flight hardware development and certification issues. This will minimize changes between ground and flight components, and will familiarize the team with the engineering requirements and objectives. Third, the PSI *MADE* Project Manager, Dr. Javier de Luis, will participate in all engineering discussions and meetings at CU, serving as a conduit between the engineering science and the flight hardware development.

5.5.2 Integration Documentation and Control

The Payload Systems *MADE* team has extensive experience working in the Space Shuttle environment, and is intimately familiar with all integration documentation and requirements. We anticipate the following documents will be required: Form 1628; Payload Integration Plan and Annexes; and the Interface Control Document. Our approach will be to initiate productive interaction with all appropriate JSC integration personnel early in Phase B; the excellent working relationship between PSI and JSC will contribute to the speed and accuracy of this process. *MADE* review and briefing requirements also will depend on close communication with the organizations concerned. All *MADE* reviews, launch and mission operations will be supported by appropriate team members at the necessary sites.

In addition to integration documentation and meetings, the *MADE* team will support the Phase Safety Process. The same philosophy applied to integration tasks will be applied to safety: the *MADE* Integration Engineer will establish contact with the appropriate safety personnel immediately following 1628 approval. The *MADE* team will support Phases 0 through III Safety Reviews and will prepare exhaustive Safety Data Packages at each phase to minimize the potential for late payload redesign. This is the same method applied to MODE and MACE. MODE not only successfully completed the Phase Safety Review process with a minimum of action items, but the Payload Safety Review Panel deemed the MODE Phase II Safety Data Package so complete as to make a Phase II meeting superfluous, and subsequently canceled the review. Similarly, MACE Phase O and Phase I meetings were completed with minimal comments.

Without close cooperation with the carrier organizations concerned, *MADE* interface, resource, and operations requirements could severely limit manifesting opportunities, thus prolonging the project schedule by months. Therefore the Integration Engineer will place especial emphasis on early and frequent contact with the appropriate NASA personnel. By maintaining close interaction with these organizations, we anticipate successful completion of all *MADE* carrier integration tasks within a complex secondary payload integration schedule.

5.5.3 Reporting, Meetings, and Reviews

The success of *MADE* will depend on excellent communication both within the team and with external organizations. To ensure seamless communication within the team, informal communication lines will be supplemented by a rigorous reporting structure. Weekly Project Team Telecons between CU, PSI, and LaRC will provide the team members with a regular opportunity to discuss task progress and will help to ensure early detection and resolution of schedule and technical problems. Monthly Telecons with NASA will commence in Phase B with the appointment of a NASA Contract Monitor, and will provide the Contract Monitor with regular technical and financial status updates. Monthly Technical and Financial Reports and Quarterly Financial Reports (533 M and 533 Q) will be prepared by the PI based on status reports from PSI and submitted to the NASA Contract Monitor. Finally, Scheduled Project Reviews will include the Requirements Review/Conceptual Design Review, Preliminary Design Review, Critical Design Review, Acceptance Review, and Final Presentation as well as Interface Control Document/Payload Integration Plan Meeting and Phase Safety Reviews. Supporting materials will be provided to the NASA Contract Monitor in advance of each review.

5.5.4 Sub-Contractor Management

The PSI *MADE* Project Manager will report to the PI on technical matters at the biweekly project team meeting. Financial control of the subcontracts will be handled by the CU. PSI will submit monthly billing statements and updated cost projections, which the PI will include in the financial reports submitted to NASA.

5.5.5 Fiscal Control and Procurement

The University of Colorado will be responsible for fiscal control for *MADE*. CU will prepare and submit Monthly and Quarterly Financial Reports (533M and Q) to NASA. CU will require PSI to submit similar reports which will also be forwarded to NASA for review. Information from these reports will be used to anticipate cost profiles and funding requirements. Payload Systems will be responsible for the purchase of flight instrument hardware components. Their extensive flight hardware experience has resulted in a large network of reliable, experienced suppliers who can deliver on-time and at reasonable cost. For all purchases over $1,000, PSI will solicit competing bids from multiple suppliers. NASA LaRC will be responsible for procurement of all test article hardware components.

5.5.6 Schedule, Budget and Tasks

The *MADE* schedule is extremely ambitious for the science, development, and integration complexity *MADE* will entail. In recognition of this fact, CU, PSI, and LaRC will strictly monitor *MADE* schedules, budgets, and task progress, to identify and resolve potential scientific or technical problems at an early stage and with minimum impact to the project. The PI/Project Manager, the LaRC Co-PI, and the PSI Project Manager will prepare an Implementation Plan that will serve as the source document for all management actions for the *MADE* project. The plan will outline the task, schedule, and cost plans for Phases B and C/D, along with corresponding controls. The PI/Project Manager will work with the Project Administrator to track the status of all contract-related tasks through automatically generated weekly and monthly accounting reports. PSI will supply sufficient status information to enable the PI/Project Manager to monitor the weekly progress of all flight systems and integration tasks.

6.0 SUMMARY AND CONCLUSIONS

The *MADE* flight program will collect critical data which will directly enable the deployment of high precision sensor elements from compact spacecraft packages. Without the flight, the ground-developed technology will not be used in production spacecraft. With the flight, not only will a single point validation be collected, but data will also be collected which extends the *MADE* technology to other configurations.

The *MADE* Phase A Feasibility study paid close attention to the concerns raised by the proposal reviewers in the previous round of selections. These concerns were communicated in the official NASA Oral Debriefing on January 26, 1994. Each concern is listed in Table 10 with a list of the actions taken.

TABLE 10. *MADE* was Reconfigured in Response to Reviewers' Oral Debriefing Feedback

Concern at Oral Debriefing	Response and Actions Taken
Scope may be too large.	See Table 9 on page 19 for descoping options that were considered.
Deployment should avoid violation of Shuttle dynamic envelope.	See Section 2.4.6 on page 19.
No technology transfer plan	See Section 1.6 on page 9 and Section 2.5 on page 20.
No 1-g testing to be correlated with 0-g testing	See Section 2.1.4 on page 13.
Post-flight activities need clarification	Section 2.2.3 on page 15.
Cost was over AO	See Volume II.
No mission criticality	See Section 1.4 on page 8.
Minimal application to non-aerospace industries	See Section 1.5 on page 8.
Team may be too large	See Section 5.2 on page 22.

The *MADE* team looks forward to a successful review with the greatest possible enthusiasm for a positive outcome. We believe strongly in the potential this program has to provide a singularly important contribution to the future of spaceflight.

CU Proposal No. 0395.08.0402B

CONTRACT PRICING PROPOSAL COVER SHEET

1. SOLICITATION/CONTRACT/MODIFICATION NO.

FORM APPROVED OMB NO. 9000-0013

NOTE: This form is used in contract actions if submission of cost or pricing data is required. *(See FAR 15.804-6(b))*

2. NAME AND ADDRESS OF OFFEROR *(Include ZIP Code)*

The Regents of the University of Colorado
Campus Box 19
Boulder, CO 80309-0019

3A. NAME AND TITLE OF OFFEROR'S POINT OF CONTACT

Lee Peterson, Assistant Professor

3B. TELEPHONE NO.

(303) 492-1743

4. TYPE OF CONTRACT ACTION *(Check)*

☐ A. NEW CONTRACT
☐ B. CHANGE ORDER
☐ C. PRICE REVISION/ REDETERMINATION
☐ D. LETTER CONTRACT
☐ E. UNPRICED ORDER
☐ F. OTHER *(Specify)*

5. TYPE OF CONTRACT *(Check)*

☐ FFP ☐ CPFF ☐ CPIF ☐ CPAF
☐ FPI ☒ OTHER *(Specify)* Cost-Reimbursable

6. PROPOSED COST *(A+B=C)*

A. COST	B. PROFIT/FEE	C. TOTAL
$3,756,700	$ 0	$3,756,700

7. PLACE(S) AND PERIOD(S) OF PERFORMANCE

Center for Space Construction, Department of Aerospace Engineering Sciences
University of Colorado, Boulder, CO 80309 07/01/95 — 12/31/98

8. List and reference the identification, quantity and total price proposed for each contract line item. A line item cost breakdown supporting this recap is required unless otherwise specified by the Contracting Officer. *(Continue on reverse, and then on plain paper, if necessary. Use same headings.)*

A. LINE ITEM NO.	B. IDENTIFICATION	C. QUANTITY	D. TOTAL PRICE	E. REF.
A.	Salaries and Wages		468,824	
B.	Fringe Benefits		85,529	
C.	Travel		30,000	
D.	Equipment		143,500	
E.	Subcontract: Payload Systems		2,617,020	
F.	Other Direct Costs		110,328	
G.	Indirect Costs		301,499	
H.	**Total Costs**		**$3,756,700**	

9. PROVIDE NAME, ADDRESS, AND TELEPHONE NUMBER FOR THE FOLLOWING *(If available)*

A. CONTRACT ADMINISTRATION OFFICE

Robert J. Silverman, Regional Director
ONR Regional Office, University of Washington
1107 NE 45th Street, Suite 350
Seattle, WA 98105-4631 (206) 526-3168

B. AUDIT OFFICE

Vincent Imbriani, Cognizant Auditors, Region 7
Office of the Inspector General, H&HS
601 East 12th Street, P.O. Box 15687
Kansas City, MO 64106 (816) 426-7253

10. WILL YOU REQUIRE THE USE OF ANY GOVERNMENT PROPERTY IN THE PERFORMANCE OF THIS WORK? *(If "Yes," identify)*

☐ YES ☒ NO

11A. DO YOU REQUIRE GOVERNMENT CONTRACT FINANCING TO PERFORM THIS PROPOSED CONTRACT? *(If "Yes," complete Item 11b)*

☐ YES ☐ NO

11B. TYPE OF FINANCING *(√ one)*

☐ ADVANCE PAYMENTS ☐ PROGRESS PAYMENTS
☐ GUARANTEED LOANS

12. HAVE YOU BEEN AWARDED ANY CONTRACTS OR SUBCONTRACTS FOR THE SAME OR SIMILAR ITEMS WITHIN THE PAST 3 YEARS? *(If "Yes," identify item(s), customer(s) and contract number(s))*

☒ YES ☐ NO

NASW-4873, "Micron Accuracy Deployment Experiment",
NASA, 07/01/94 — 03/31/95

13. IS THIS PROPOSAL CONSISTENT WITH YOUR ESTABLISHED ESTIMATING AND ACCOUNTING PRACTICES AND PROCEDURES AND FAR PART 31 COST PRINCIPLES? *(If "No," explain)*

☒ YES ☐ NO

14. COST ACCOUNTING STANDARDS BOARD (CASB) DATA *(Public Law 91-379 as amended and FAR PART 30)*

A. WILL THIS CONTRACT ACTION BE SUBJECT TO CASB REGULATIONS? *(If "No," explain in proposal)*

☐ YES ☒ NO Educational Institution

B. HAVE YOU SUBMITTED A CASB DISCLOSURE STATEMENT *(CASB DS-1 or 2)? (If "Yes," specify in proposal the office to which submitted and if determined to be adequate)*

☐ YES ☐ NO N/A

C. HAVE YOU BEEN NOTIFIED THAT YOU ARE OR MAY BE IN NON-COMPLIANCE WITH YOUR DISCLOSURE STATEMENT OR COST ACCOUNTING STANDARDS? *(If "Yes," explain in proposal)*

☐ YES ☐ NO N/A

D. IS ANY ASPECT OF THIS PROPOSAL INCONSISTENT WITH YOUR DISCLOSED PRACTICES OR APPLICABLE COST ACCOUNTING STANDARDS? *(If "Yes," explain in proposal)*

☐ YES ☐ NO N/A

This proposal is submitted in response to the RFP, contract, modification, etc. in Item 1 and reflects our best estimates and/or actual costs as of this date and conforms with the instructions in FAR 15.801 6(b) (2), Table 15-2. By submitting this proposal, the offeror, if selected for negotiation, grants the contracting officer or an authorized representative the right to examine, at any time before award, those books, records, documents and other types of factual information, regardless of form or whether such supporting information is specifically referenced or included in the proposal as the basis for pricing, that will permit an adequate evaluation of the proposed price.

15. NAME AND TITLE *(Type)*

David R. Kassoy
Associate Vice Chancellor for Academic Affairs

16. NAME OF FIRM

The Regents of the University of Colorado

17. SIGNATURE

DRKassoy

18. DATE OF SUBMISSION

VOLUME II: RESOURCES PLAN FOR THE MICRON ACCURACY DEPLOYMENT EXPERIMENT (*MADE*)

1.0 SUMMARY

The Resources Plan shown in Attachments B and C is based on the scientific and technical efforts outlined in Volume I. Broadly stated, the work breakdown is as follows:

- **CU (UNIVERSITY OF COLORADO)**
  Principal Investigator organization responsible for *MADE* management, systems engineering, and overall engineering science.
- **LARC (NASA LANGLEY RESEARCH CENTER)**
  Co-Principal Investigator organization responsible for *MADE* test article design, procurement, and construction. Shared responsibility for program engineering science.
- **PSI (PAYLOAD SYSTEMS INC.)**
  Subcontractor to CU responsible for design and construction of flight instrumentation and data collection systems, as well as for flight experiment integration.

Please note that, contractually, PSI is a subcontractor to CU, while LaRC receives its funding directly from InSTEP. However, CU and LaRC will coordinate budget and schedule information to ensure successful management of this project. This Resources Plan represents an official budget proposal (see attached Form 1411) with terms being effective 4/1/95 to 10/1/95. A 7/1/95 start date is assumed.

2.0 RESOURCES PLAN REALISM

This Resource Plan was developed by a breakdown of individual program tasks where necessary to Level 5. Labor requirements were based on the extensive flight experience of PSI and the level of effort required to support the science development efforts. Hardware costs were determined using verbal quotes from manufacturers.

A major factor in judging the realism of the proposed budget is the extensive hardware prototyping and testing done during Phase A.

3.0 FISCAL CONTROL

MADE contractual affairs will be administered by CU's Office of Contracts and Grants. CU Sponsored research accounts are monitored and audited annually by the State of Colorado for fiscal compliance. PSI uses the government-approved Deltek accounting system. All projects are monitored by task and product. Procurements of over $1,000 must be competitively bid, unless approved by the corporate president.

4.0 NON-IN-STEP FUNDING

Three Graduate Student RA's whose research directly supports the ground based science effort behind the *MADE* flight program are not funded directly by In-STEP. NASA Grant NGT-10033, the Center for Space Construction Graduate Training Program, provides $16K annual support per student through 10/31/97. These are in addition to the Graduate Researchers called out in Table 2.

5.0 DIRECT LABOR RATES

The labor rates of the actual individuals assigned to work on the program have been used by CU, PSI and LaRC to develop the cost plan. When new personnel are to be hired, a rate commensurate with the expected salary level is projected for that individual.

CU. Labor rates and fringe benefits are determined according to standard University practice. The labor rates of the individuals used in this proposal may be verified by requesting information from the CU Office of Contracts and Grants.

LARC. NASA Langley Travel and Direct Labor costs are not charged to this program. Note that they appear in Attachment C but are not included in the totals. This is indicated by the "non add" label in Attachment C. The overhead fractions are, however, included.

PSI. The labor rates of the individuals used in this proposal may be verified by requesting information from the local DCAA Auditor.

6.0 INDIRECT RATES

The CU employee benefit and indirect expense rates are:

- Undergraduate students 1.9%
- Graduate Students 3.36% + $420 per year for insurance
- Staff: 23%

The Indirect Expense (IE) is applied to the Modified Total Direct Cost (MTDC) base in accordance with the OMB circular A21. The rates for the University are those negotiated with the U.S. Department of Health and Human Services on 10/23/93. Each year the rates billed will be the approved negotiated rates for that year and may differ from the above.

7.0 PROGRAM CONTINGENCY

The *MADE* team feels that it is important to specify budget contingency as an indication of the potential overrun that could occur in the development and procurement of certain high risk items. Notice that a detailed design and evaluation exercise was conducted in Phase A in order to reduce the risk of such overruns. While this contingency is not included in the budgets summarized in Attachments B and C, a 10% increase in the budget concentrated primarily in FY 1996 and 1997 should cover all unforeseen hardware design and procurement difficulties. The maturity of the Conceptual Design Document and the Implementation Plan warrants this level of contingency.

8.0 COST TABLES

The following tables contain all costing information requested in the Guidelines for In-STEP Phase A Deliverables. All cost items are tied directly to the WBS and summarized by task and phase in the Attachments. All cost estimates are based on the best information of the *MADE* team at the time of submission, and reflect the experience of the team in designing, fabricating, certifying, and performing successful flight experiments on the Shuttle. As

MADE will be a Class D payload, commercial off-the-shelf (COTS) parts will be used where possible. We do not presently anticipate the procurement of any parts with longer lead times than 24 weeks. A detailed assessment of critical, long lead time items will be conducted early in Phase B. Cost estimates for parts and travel reflect current prices and fares.

Attachments B and C are included at the end of this Resources Plan. In addition, three tables providing additional cost detail have been provided: direct labor, materials, and travel. Costs in these supporting tables are unburdened values, so that direct comparisons with Attachments B and C can be made. Information is presented broken out by *MADE* partner and appropriate category.

8.1 Material List

Table 1 contains the major equipment costs. All significant major items are included. Miscellaneous items (fasteners, cabling, connectors, etc.), are accounted for within each major component. A phase by phase breakout is not provided since some procurements extend across several phases.

8.2 Direct Labor

Table 2 describes the break out, by job category, for the entire *MADE* program. A number greater than 100% in a job category indicates more than one individual is in that category. Percentages represent an average level of staffing and do not reflect variations inherent in any flight development program. The table is subdivided showing CU, PSI, and LaRC labor costs. The costs are unburdened and can be compared directly with Attachment B.

The indicated support for CU secretarial, purchasing, and accounting personnel is required because the Center for Space Construction, as an independent research center within the University, has no institutional or departmental support for these functions. Research contracts must therefore include direct support for these duties as they relate to the individual contract. The support shown in Table 2 for these administrative tasks are commensurate with the level of effort represented in the tasks described in Volume I.

8.3 Travel

Table 3 describes the expected travel costs for *MADE* including the relevant event, the number of trips, duration, and number of people. We have presumed that LaRC will be the NASA center assigned oversight of *MADE*. For the purposes of this budget, it was assumed that some support would be required at all major reviews, either at JSC or KSC. The *MADE* team will also endeavor to utilize video and teleconferencing as much as possible to reduce the total travel cost of this program.

In general, the table shows CU supporting all managerial, design, and programmatic reviews, as well as hardware delivery operations and recovery. They support only a subset of integration and training reviews. PSI supports all integration and safety reviews, as well as appropriate design and program meetings, and travel associated with testing and delivery. LaRC and CU support the same managerial, design, and programmatic reviews.

9.0 ATTACHMENT B

Attachment B shows program cost in FY95 dollars for each level three WBS item for each fiscal year in each Phase. Subtotals are provided across the phases.

TABLE 1 Material List by Phase

	Equipment	WBS	Phase	*Cost
CU	Breadboard Flight Metrology System	3.2	B	10.0
	12DOF Laser Interferometer	2.1,3.2	B	35.0
	Repeatable Impulse Hammer	2.1,2.2	B	2.0
	Breadboard Flight Latchuator	3.1	B	15.0
	Science Instrumentation	2.1,2.2	B	7.5
	Video Telecomm Equipment	2.1	B	10.0
	Science Instrumentation	2.1,3.2	C/D	24.0
	Flight Science Integration Hardware	4.1	C/D	30.0
	Flight Data Storage System	6.1-6.4	C/D	10.0
PSI	Shipping, Handling, and Test	3.6	B	2.4
	Verification Activities	4.2	B	6.3
	Metrology System	3.2	C/D	9.0
	Deployment Mechanics Sen Sys	3.2	C/D	11.4
	Vibration Instrumentation Sys	3.2	C/D	13.4
	Environmental Instrumtn Sys	3.2	C/D	23.8
	Mechanical Interface	3.3	C/D	23.0
	Electrical Interface	3.3	C/D	7.1
	Structure/Containment	3.4	C/D	8.6
	Experiment Control Computer	3.4	C/D	26.7
	Signal Conditioning System	3.4	C/D	61.1
	Data Handling & Storage Sys	3.4	C/D	20.4
	Power Distribution System	3.4	C/D	24.1
	ESM Assembly & Integration	3.4	C/D	3.8
	Shipping, Handling, & Test	3.6	C/D	83.5
	Ground Station	3.6	C/D	36.6
	Verification Activities	4.2	C/D	30.6
	Total CU and PSI (THOUSANDS):			*535.1*
LaRC	Sensors	3.1	B	20.0
	Engineering Model Modifications	3.1	B	34.7
	Reflector Panels	3.1	C/D	110.1
	Deployment Actuators	3.1	C/D	330.3
	Panel Actuators	3.1	C/D	82.6
	Metering Truss Purchased Parts	3.1-4.1	C/D	84.9
	Total Langley (THOUSANDS):			*662.6*
	Total Program (THOUSANDS):			*1197.7*

**** All costs are in thousands.***

10.0 ATTACHMENT C

Attachment C shows the *MADE* budget in terms of cost categories for each level three WBS task. Since CU and PSI have different overhead structures, labor overhead is not a fixed percentage of direct labor. Direct labor represents salary while labor overhead includes overhead and employee benefits. Subcontractors to PSI have a maximum of a 9% fee which is identical to that charged on previous In-STEPs in which PSI had a role. CU's Other Costs include Graduate RA tuition and overhead-bearing expendable materials and services.

TABLE 2 Labor Summary

	Employee	Phase B %	Phase B Hrs.	Phase B *Cost	Phase C/D %	Phase C/D Hrs.	Phase C/D *Cost	Totals Hrs.	Totals *Cost
CU	Principal Investigator	44%	763	27.1	50%	2,756	112.1	3,519	139.3
	Faculty 1	9%	156	9.2	8%	459	30.8	615	40.0
	Faculty 2	9%	156	7.1	8%	459	23.6	615	30.7
	Faculty 3	8%	139	3.4	8%	444	11.5	583	14.9
	Lab Technician	25%	433	10.6	25%	1,387	36.5	1,820	47.1
	Graduate Researcher 1	60%	1,040	12.3	64%	3,553	48.8	4,593	61.1
	Graduate Researcher 2	60%	1,040	12.3	64%	3,553	48.8	4,593	61.1
	Undergraduate Researchers	23%	400	3.2	26%	1,440	11.5	1,840	14.7
	Administrative Assistant	25%	433	7.7	25%	1,387	26.4	1,820	34.1
	Secretary	20%	347	5.8	20%	1,109	19.9	1,456	25.7
	Univ. of Colorado Totals:		*4,907*	*98.7*		*16,547*	*370.1*	*21,454*	*468.8*
PSI	Project Manager	31%	472	16.8	25%	986	35.0	1,458	51.8
	Administrative Assistant	3%	40	0.6	3%	116	1.8	156	2.4
	Quality Assurance Engineer	5%	76	2.7	9%	348	12.2	424	14.8
	Electrical Engineer 1	43%	660	18.2	51%	2,050	56.5	2,710	74.7
	Electrical Engineer 2	15%	228	3.8	60%	2,386	40.2	2,614	44.0
	Integration Manager	27%	412	6.5	70%	2,788	44.0	3,200	50.6
	Mechanical Engineer 1	57%	868	28.4	88%	3,500	114.3	4,368	142.7
	Mechanical Engineer 2	22%	340	7.6	63%	2,518	56.5	2,858	64.2
	Software Engineer 1	29%	442	12.7	63%	2,498	71.5	2,940	84.2
	Software Engineer 2	5%	84	1.8	44%	1,746	37.8	1,830	39.6
	Technician 1	0%	-	-	48%	1,904	32.1	1,904	32.1
	Technician 2	0%	-	-	62%	2,480	41.8	2,480	41.8
	PSI Totals:		*3,622*	*99.0*		*23,320*	*543.7*	*26,942*	*642.8*
	Total Program (Univ. of Colorado & PSI):		*8,529*	*197.7*		*39,867*	*913.8*	*48,396*	*1,111.6*
Langley	Project Management	30%	460	22.6	29%	1,420	73.6	1,880	96.2
	Co-Principal Investigator	100%	1,533	69.9	100%	4,907	243.2	6,440	313.1
	Research Engineer	119%	1,827	83.3	76%	3,728	184.8	5,555	268.1
	Engineering	135%	2,066	94.8	29%	1,413	66.8	3,479	161.6
	Technician	59%	909	25.2	26%	1,267	35.8	2,176	61.0
	Admin Professional	13%	205	6.4	28%	1,370	37.6	1,575	44.0
	Secretarial	5%	80	1.2	4%	200	1.9	280	3.1
	Langley Totals (Non-Add costs):		*7,080*	*303.4 ***		*14,305*	*643.7 ***	*21,385*	*947.1 ***

All costs are in thousands.* * Langley labor costs not added to total.*

11.0 SUMMARY

The required *MADE* costs described in this Resources Plan are a realistic estimate of the cost required to accomplish the technical goals stated in Volume I. The total Phases B/C/D amount has grown since the original Phase A contract by approximately 13%. Some of this is due to inflation in salaries and material costs during the 18 month delay between the original planned procurement and the current schedule. The remaining additional costs are primarily due to the fact that Phase A was bid at a time when NASA would be providing indirect staff support through the Center for Space Construction. Since the block grants for all Space Engineering Research Centers have ended, individual contracts, such as *MADE*, must bear these costs.

The *MADE* team believes that it has achieved a high level of maturity in the flight objectives, flight justification, and hardware design during Phase A. The tremendous technical potential reported in Volume I justifies the appropriate level of expenditure requested in this plan, and NASA can be assured of a valuable return on this investment.

TABLE 3 Travel List by Phase

	From	To	No. of Trips	No. of People	No. of Days	Purpose	*Cost (000)
CU Phase B	Boulder, CO	Hampton, VA	1	2	2	RR	1.5
	Boulder, CO	Hampton, VA	1	2	2	PDR	1.5
	Boulder, CO	Washington, DC	1	1	2	NAR	1.0
	Boulder, CO	Houston, TX	1	1	1	Phase 0/I Safety Review	0.8
						Total CU Phase B	*4.8*
CU Phase C/D	Boulder, CO	Hampton, VA	1	3	2	CDR	2.3
	Boulder, CO	Hampton, VA	1	1	3	FRR	0.8
	Boulder, CO	Houston, TX	2	1	2	Phase II & III Safety Reviews	2.0
	Boulder, CO	Orlando, FL	1	3	3	Pre-Launch Support	3.0
	Boulder, CO	Washington, DC	1	4	12	Mission Operations	8.0
	Boulder, CO	Washington, DC	1	3	2	GSFC Integration Reviews	0.8
	Boulder, CO	Houston, TX	4	1	2	JSC Integration Reviews	4.0
	Boulder, CO	Orlando, FL	1	2	2	Hardware Recovery (@KSC)	1.5
	Boulder, CO	Washington, DC	1	3	2	Post-Mission Review	3.0
						CU Phase C/D	*25.3*
PSI PhaseB	Boston	Boulder, CO	1	3	2	TIM	*5.4*
	Boston	Hampton, VA	1	3	3	PDR	*2.4*
	Boston	Hampton, VA	1	2	2	RR	*1.4*
	Boston	Washington, DC	1	2	1	NAR	*1.6*
	Boston	Washington, DC	1	1	2	Prepare Phase 0/I SDP	*1.0*
	Boston	Houston, TX	1	3	2	Phase 0/I Safety Review	*4.3*
						PSI Phase B	*16.2*
PSI Phase C/D	Boston	Boulder, CO	2	3	2	TIM	10.8
	Boston	Hampton, VA	1	3	3	CDR	2.4
	Boston	Hampton, VA	1	2	2	FRR	1.4
	Boston	Hampton, VA	2	2	15	Vibration Testing	7.0
	Boston	Houston TX	2	2	7	EMI/EMC Testing	6.5
	Boston	Hampton, VA	2	2	11	Thermal Testing	6.8
	Boston	Orlando FL	4	2	2	Integration Reviews	6.9
	Boston	Washington, DC	1	1	3	Prepare Phase II SDP	1.2
	Boston	Houston, TX	2	5	2	Phase II & III Safety Reviews	12.9
	Boston	Washington, DC	3	1	2	PIP Negotiations	3.5
	Boston	Houston, TX	1	1	2	ICD Review	1.5
	Boston	Houston	4	2	2	Crew Training	11.7
	Boston	GSFC	3	3	10	Hardware Delivery	18.1
	Boston	Orlando FL	1	2	5	Pre-Launch Support	2.4
	Boston	Washington, DC	1	3	12	Mission Operations	7.6
	Boston	Orlando FL	1	1	2	Hardware Recovery (@ KSC)	0.9
	Boston	Washington DC	2	2	6	Hardware Recovery (@ GSFC)	7.4
						Total PSI Phase C/D	*109.1*
						Program Phase B (CU and PSI)	*20.9*
						Program Phase C/D (CU and PSI)	*134.3*
						Total Program Phase B and C/D (CU and PSI)	***155.3***
Langley Phase B							
	Hampton, VA	Washington DC	1	3	1	NAR	*1.8*
	Hampton, VA	Los Angeles	1	2	2	Able Eng.	*1.6*
	Hampton, VA	Colorado	1	2	2	TIM	*1.5*
	Hampton, VA	NASA JSC	1	1	2	Phase 0/1 Safety Review	*0.8*
						Langley Phase B (Non-Add)	*5.7 ***
Langley Phase C/D	Hampton, VA	Washington DC	1	2	1	HQ Briefing	1.3
	Hampton, VA	Colorado	1	2	14	On-Site Integration	4.6
	Hampton, VA	NASA JSC	1	1	5	Crew	1.9
	Hampton, VA	NASA JSC	4	1	2	Safety (Integration)	3.1
	Hampton, VA	NASA KSC	3	1	2	KSC Integ.	1.4
	Hampton, VA	NASA KSC	1	2	7	Launch Support	3.3
	Hampton, VA	NASA KSC	1	2	5	Pre-Launch Support	2.4
	Hampton, VA	NASA GSFC	1	1	10	Integration	1.8
	Hampton, VA	NASA GSFC	1	2	12	Operation	4.4
	Hampton, VA	NASA GSFC	1	2	6	Recovery	2.2
						Langley Phase C/D (Non-Add)	*26.4 ***
						Langley Phase B and C/D (Non-Add)	*32.1 ***

****All costs are in thousands.* *** Langley travel costs not added to total.***

EXPERIMENT COST PLANNING - COSTS BY FISCAL YEAR BY WBS ELEMENT **Attachment B**

WBS Element	B (FY95) TOTAL	B (FY96) TOTAL	**Phase B TOTAL**	C/D (FY96) TOTAL	C/D (FY97) TOTAL	C/D (FY98) TOTAL	C/D (FY99) TOTAL	**Phase C/D TOTAL**	**GRAND TOTAL** (All Phases)
Univ. of Colorado & PSI									
1 Project Management	**25.6**	**55.8**	**81.4**	**43.8**	**85.7**	**85.7**	**6.2**	**221.5**	**302.9**
1.1 Project Planning & Schedule	1.0	2.2	3.2	1.9	4.7	4.7	-	11.3	14.4
1.2 Financial Management & Reporting	5.6	13.0	18.6	10.7	25.8	25.8	-	62.3	80.9
1.3 Task Management & Tracking	3.6	8.4	11.9	6.6	15.8	15.8	3.9	42.1	54.1
1.4 Customer Interface	2.1	5.0	7.1	3.8	9.2	9.2	2.3	24.4	31.5
1.5 LaRC Management	-	-	-	-	-	-	-	-	-
1.6 Integration Subcontractor Mangmt	13.3	22.7	36.0	18.9	25.4	25.4	-	69.7	105.6
1.7 Quality	-	4.6	4.6	1.9	5.0	5.0	-	11.8	16.4
2 System Engineering	**63.2**	**223.7**	**286.9**	**184.7**	**180.7**	**197.4**	**37.6**	**600.4**	**887.3**
2.1 Engineering Science	38.4	89.5	127.9	49.0	117.5	117.5	29.4	313.4	441.3
2.2 Requirements Definition	8.8	36.1	44.9	31.7	-	-	-	31.7	76.6
2.3 Configuration Management	7.2	35.2	42.3	41.2	31.0	38.1	0.2	110.4	152.8
2.4 Commercialization & Tech Tsfr	5.2	12.1	17.3	9.3	22.2	22.2	5.6	59.3	76.6
2.5 Program Reviews	3.7	50.8	54.5	53.6	9.9	19.6	2.5	85.6	140.0
3 Design & Fabrication	**46.9**	**138.8**	**185.7**	**338.4**	**736.6**	**131.7**	-	**1,206.7**	**1,392.5**
3.1 Test Article	7.3	17.0	24.3	8.6	20.6	-	-	29.2	53.5
3.2 Instrumentation	16.4	38.2	54.6	40.9	157.6	-	-	198.5	253.1
3.3 MPESS Interface	5.2	10.4	15.6	17.3	57.9	-	-	75.2	90.8
3.4 Experiment Support Module	16.6	51.0	67.6	183.9	239.5	23.3	-	446.8	514.4
3.5 Software	1.4	10.7	12.0	33.4	110.1	66.7	-	210.2	222.2
3.6 GSE	-	11.6	11.6	54.3	151.0	41.6	-	246.9	258.5
4 Integration & Verification	**6.0**	**62.2**	**68.2**	**54.9**	**360.2**	**395.2**	-	**810.3**	**878.5**
4.1 Flight Experiment Integration	-	9.8	9.8	20.1	188.7	199.6	-	408.4	418.2
4.2 Carrier Integration	6.0	52.4	58.4	34.9	171.5	195.6	-	401.9	460.4
5 Operations	-	**6.1**	**6.1**	**6.7**	**11.7**	**219.0**	-	**237.4**	**243.5**
5.1 Experiment On-Orbit Procedures	-	3.1	3.1	3.7	8.3	13.0	-	25.0	28.1
5.2 Mission Operations	-	3.0	3.0	3.0	3.4	205.9	-	212.4	215.4
6 Data Analysis & Reporting	-	-	-	-	-	-	**52.0**	**52.0**	**52.0**
6.1 Archiving	-	-	-	-	-	-	6.2	6.2	6.2
6.2 Per Analysis vs Obj	-	-	-	-	-	-	17.8	17.8	17.8
6.3 Per Analysis vs Cust	-	-	-	-	-	-	12.3	12.3	12.3
6.4 Reporting	-	-	-	-	-	-	15.7	15.7	15.7
TOTAL PRICE (PSI & CU)	**141.7**	**486.6**	**628.3**	**628.6**	**1,374.9**	**1,029.0**	**95.8**	**3,128.4**	**3,756.7**
Langley									
1 Project Management	**4.2**	**22.0**	**26.2**	**38.2**	**31.8**	**33.2**	**5.2**	**108.4**	**134.6**
1.1 Project Planning & Schedule	3.2	14.0	17.2	-	-	-	-	-	17.2
1.2 Financial Management & Reporting	-	-	-	-	-	-	-	-	-
1.3 Task Management & Tracking	-	-	-	-	-	-	-	-	-
1.4 Customer Interface	-	-	-	-	-	-	-	-	-
1.5 LaRC Management	-	-	-	35.2	27.8	30.2	5.2	98.4	98.4
1.6 Integration Subcontractor Mangmt	-	-	-	-	-	-	-	-	-
1.7 Quality	1.0	8.0	9.0	3.0	4.0	3.0	-	10.0	19.0
2 System Engineering	**4.2**	**4.7**	**8.9**	**3.2**	-	-	-	**3.2**	**12.1**
2.1 Engineering Science	-	-	-	-	-	-	-	-	-
2.2 Requirements Definition	2.6	-	2.6	-	-	-	-	-	2.6
2.3 Configuration Management	1.6	1.6	3.2	-	-	-	-	-	3.2
2.4 Commercialization & Tech Tsfr	-	-	-	-	-	-	-	-	-
2.5 Program Reviews	-	3.1	3.1	3.2	-	-	-	3.2	6.3
3 Design & Fabrication	**44.6**	**110.5**	**155.1**	**106.5**	**644.4**	-	-	**750.9**	**906.0**
3.1 Test Article	44.6	110.5	155.1	106.5	644.4	-	-	750.9	906.0
3.2 Instrumentation	-	-	-	-	-	-	-	-	-
3.3 MPESS Interface	-	-	-	-	-	-	-	-	-
3.4 Experiment Support Module	-	-	-	-	-	-	-	-	-
3.5 Software	-	-	-	-	-	-	-	-	-
3.6 GSE	-	-	-	-	-	-	-	-	-
4 Integration & Verification	-	**3.2**	**3.2**	-	**64.2**	**5.9**	-	**70.1**	**73.3**
4.1 Flight Experiment Integration	-	-	-	-	60.9	0.8	-	61.7	61.7
4.2 Carrier Integration	-	3.2	3.2	-	3.3	5.1	-	8.4	11.6
5 Operations	-	**1.6**	**1.6**	**1.6**	**3.3**	**13.3**	-	**18.2**	**19.8**
5.1 Experiment On-Orbit Procedures	-	1.6	1.6	1.6	3.3	0.8	-	5.7	7.3
5.2 Mission Operations	-	-	-	-	-	12.5	-	12.5	12.5
6 Data Analysis & Reporting	-	-	-	-	-	**2.5**	**27.2**	**29.7**	**29.7**
6.1 Archiving	-	-	-	-	-	2.5	3.4	5.9	5.9
6.2 Per Analysis vs Obj	-	-	-	-	-	-	7.7	7.7	7.7
6.3 Per Analysis vs Cust	-	-	-	-	-	-	7.7	7.7	7.7
6.4 Reporting	-	-	-	-	-	-	8.4	8.4	8.4
TOTAL PRICE (Langley)	**53.0**	**142.0**	**195.0**	**149.5**	**743.7**	**54.9**	**32.4**	**980.5**	**1,175.5**
TOTAL PROJECT PRICE	**194.7**	**628.6**	**823.3**	**778.1**	**2,118.6**	**1,084.0**	**128.2**	**4,108.9**	**4,932.2**

Attachment C: The table below show costs broken out by WBS elements and categories. Similar to Attachment B, CU and PSI costs are combined, with Langley costs shown separately. The last section of the table shows the program summary. Direct Labor represents the actual personnel salaries. Employee benefits and Overhead is applied to direct labor. Indirect costs are applied to labor, employee benefits and overhead, travel, and materials and services. In the CU and PSI table, fee is 9% of the total PSI costs for each WBS element. In the Langley table, Direct Labor and Travel are not added to the bottom line.

University of Colorado & Payload Systems Inc.

COSTS BY WORK BREAKDOWN STRUCTURE ELEMENTS (Thousands)

All numbers are in thousands	GRAND	Project Management							WBS-1	System Engineering					WBS-2	Design & Fabrication						WBS-3	Integ. & Verif.		WBS-4	Operations		WBS-5	Data Analysis & Reporting				WBS-6
	TOTALS	1.1	1.2	1.3	1.4	1.5	1.6	1.7	TOTAL	2.1	2.2	2.3	2.4	2.5	TOTAL	3.1	3.2	3.3	3.4	3.5	3.6	TOTAL	4.1	4.2	TOTAL	5.1	5.2	TOTAL	6.1	6.2	6.3	6.4	TOTAL
PHASE B PLANS																																	
Direct Labor	197.7	1.4	8.2	5.3	3.2	-	12.2	1.5	31.9	43.9	15.7	14.3	7.7	12.3	93.9	4.2	13.2	5.3	22.9	4.1	2.8	52.5	3.3	14.0	17.4	1.0	1.0	2.1	-	-	-	-	-
Labor Overhead & Fringe	129.0	0.3	2.0	1.3	0.7	-	13.6	1.7	19.6	8.2	10.1	16.0	1.9	10.6	46.7	0.9	1.3	5.9	25.5	4.5	3.1	41.3	3.7	15.3	19.0	1.2	1.1	2.3	-	-	-	-	-
Labor G&A	109.7	0.8	4.4	2.9	1.7	-	7.2	0.9	17.9	22.7	8.7	8.5	4.1	7.0	51.0	2.2	6.3	3.1	13.6	2.4	1.7	29.3	2.0	8.3	10.3	0.6	0.6	1.2	-	-	-	-	-
Direct Materials	88.2	-	-	-	-	-	-	-	-	32.3	4.8	-	-	-	37.0	15.0	27.5	-	-	-	2.4	44.9	-	6.3	6.3	-	-	-	-	-	-	-	-
Direct Travel	20.9	-	-	-	-	-	-	-	-	-	-	-	-	14.8	14.8	-	-	-	-	-	-	-	-	6.1	6.1	-	-	-	-	-	-	-	-
Other Costs (CU)	32.6	0.5	2.7	1.8	1.1	-	-	-	6.0	14.5	2.7	-	2.5	1.0	20.7	1.4	4.4	-	-	-	-	5.8	-	0.1	0.1	-	-	-	-	-	-	-	-
ODC G&A	23.2	0.2	1.2	0.8	0.5	-	-	-	2.6	6.3	1.2	-	1.1	5.2	13.8	0.6	1.9	-	-	-	0.7	3.2	-	3.6	3.6	-	-	-	-	-	-	-	-
TOTAL COST	601.4	3.2	18.6	11.9	7.1	-	33.0	4.2	78.0	127.9	43.1	38.8	17.3	51.0	278.1	24.3	54.6	14.3	62.0	11.0	10.6	176.9	9.0	53.8	62.8	2.8	2.8	5.6	-	-	-	-	-
Fee (PSI)	27.0	-	-	-	-	-	3.0	0.4	3.3	-	1.9	3.5	-	3.5	8.8	-	-	1.3	5.6	1.0	1.0	8.8	0.8	4.7	5.5	0.3	0.3	0.5	-	-	-	-	-
TOTAL Phase B (CU & PSI)	628.3	3.2	18.6	11.9	7.1	-	36.0	4.6	81.4	127.9	44.9	42.3	17.3	54.5	286.9	24.3	54.6	15.6	67.6	12.0	11.6	185.7	9.8	58.4	68.2	3.1	3.0	6.1	-	-	-	-	-
PHASE C/D PLANS																																	
Direct Labor	913.8	5.4	30.1	20.3	11.8	-	23.6	4.0	95.3	150.5	16.3	37.7	28.5	22.7	255.7	14.4	49.3	11.2	83.1	71.3	26.9	256.2	120.0	103.8	223.8	9.0	52.0	61.0	1.8	8.1	5.1	6.7	21.8
Labor Overhead & Fringe	672.7	1.3	7.1	4.8	2.7	-	26.3	4.5	46.6	28.1	2.4	41.3	6.9	15.4	94.0	2.9	18.0	12.5	92.6	79.4	30.0	235.4	129.8	106.9	236.7	8.5	48.5	57.0	0.4	0.8	0.6	1.1	2.9
Labor G&A	512.0	2.9	16.2	10.9	6.3	-	14.0	2.4	52.7	77.7	8.1	22.3	15.4	12.3	135.8	7.5	24.9	6.7	49.2	42.2	15.9	146.4	70.8	60.5	131.3	5.2	29.9	35.1	1.0	3.9	2.5	3.4	10.8
Direct Materials	446.9	-	-	-	-	-	-	-	-	12.0	-	-	-	-	12.0	-	69.5	30.1	144.6	-	120.1	364.3	30.0	30.6	60.6	-	-	-	2.5	2.5	2.5	2.5	10.0
Direct Travel	134.3	-	-	-	-	-	-	-	-	-	-	-	-	20.7	20.7	-	-	-	-	-	-	-	20.3	44.5	64.8	-	48.9	48.9	-	-	-	-	-
Other Costs (CU)	77.2	1.1	6.3	4.2	2.5	-	-	-	14.1	31.4	3.4	0.2	5.9	2.0	42.9	3.0	7.5	-	-	-	-	10.5	0.9	1.8	2.7	0.3	2.0	2.4	0.4	1.7	1.1	1.4	4.6
ODC G&A	182.3	0.5	2.7	1.8	1.1	-	-	-	6.1	13.7	1.5	0.1	2.6	7.6	25.4	1.3	19.4	8.4	40.5	-	33.6	103.2	6.1	22.8	28.9	0.2	16.5	16.7	0.2	0.7	0.5	0.6	2.0
TOTAL COST	2,939.3	11.3	62.3	42.1	24.4	-	63.9	10.8	214.8	313.4	31.7	101.5	59.3	80.7	586.6	29.2	188.6	69.0	409.9	192.8	226.5	1,116.0	377.9	370.9	748.8	23.2	197.9	221.1	6.2	17.8	12.3	15.7	52.0
Fee (PSI)	189.1	-	-	-	-	-	5.8	1.0	6.7	-	-	9.0	-	4.9	13.9	-	9.9	6.2	36.9	17.4	20.4	90.7	30.5	31.1	61.5	1.8	14.5	16.3	-	-	-	-	-
TOTAL Phase C/D (CU & PSI)	3,128.4	11.3	62.3	42.1	24.4	-	69.7	11.8	221.5	313.4	31.7	110.4	59.3	85.6	600.4	29.2	198.5	75.2	446.8	210.2	246.9	1,206.7	408.4	401.9	810.3	25.0	212.4	237.4	6.2	17.8	12.3	15.7	52.0
Total B/C/D (CU & PSI)	3,756.7	14.4	80.9	54.1	31.5	-	105.6	16.4	302.9	441.3	76.6	152.8	76.6	140.0	887.3	53.5	253.1	90.8	514.4	222.2	258.5	1,392.5	418.2	460.4	878.5	28.1	215.4	243.5	6.2	17.8	12.3	15.7	52.0

Langley

COSTS BY WORK BREAKDOWN STRUCTURE ELEMENTS (Thousands)

All numbers are in thousands	GRAND	Project Management							WBS-1	System Engineering					WBS-2	Design & Fabrication						WBS-3	Integ. & Verif.		WBS-4	Operations		WBS-5	Data Analysis & Reporting				WBS-6
	TOTALS	1.1	1.2	1.3	1.4	1.5	1.6	1.7	TOTAL	2.1	2.2	2.3	2.4	2.5	TOTAL	3.1	3.2	3.3	3.4	3.5	3.6	TOTAL	4.1	4.2	TOTAL	5.1	5.2	TOTAL	6.1	6.2	6.3	6.4	TOTAL
PHASE B PLANS																																	
Direct Labor (non-Add)	303.4	-	-	-	-	24.6	-	25.1	49.7	-	7.6	9.4	-	9.1	26.1	213.4	-	-	-	-	-	213.4	-	9.6	9.6	4.6	-	4.6	-	-	-	-	-
Overhead	113.2	-	-	-	-	10.3	-	9.0	19.3	-	2.6	3.2	-	3.1	8.9	80.2	-	-	-	-	-	80.2	-	3.2	3.2	1.6	-	1.6	-	-	-	-	-
Fabrication	15.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15.0	-	-	-	-	-	15.0	-	-	-	-	-	-	-	-	-	-	-
Materials	54.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	54.7	-	-	-	-	-	54.7	-	-	-	-	-	-	-	-	-	-	-
Subcontracts	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Special Equipment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Travel (non-Add)	5.7	-	-	-	-	0.6	-	-	0.6	-	0.4	0.4	-	0.4	1.2	3.1	-	-	-	-	-	3.1	-	0.8	0.8	-	-	-	-	-	-	-	-
Other Costs	12.1	-	-	-	-	6.9	-	-	6.9	-	-	-	-	-	-	5.2	-	-	-	-	-	5.2	-	-	-	-	-	-	-	-	-	-	-
TOTAL Phase B (Langley)	195.0	-	-	-	-	17.2	-	9.0	26.2	-	2.6	3.2	-	3.1	8.9	155.1	-	-	-	-	-	155.1	-	3.2	3.2	1.6	-	1.6	-	-	-	-	-
PHASE C/D PLANS																																	
Direct Labor (non-Add)	643.7	-	-	-	-	160.7	-	29.6	190.3	-	-	-	-	9.5	9.5	214.0	-	-	-	-	-	214.0	66.0	24.9	90.9	16.5	36.6	53.1	17.1	22.3	22.3	24.3	85.9
Overhead	235.5	-	-	-	-	61.2	-	10.0	71.2	-	-	-	-	3.2	3.2	78.8	-	-	-	-	-	78.8	26.0	8.4	34.4	5.7	12.5	18.2	5.9	7.7	7.7	8.4	29.7
Fabrication	29.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	28.1	-	-	-	-	-	28.1	1.0	-	1.0	-	-	-	-	-	-	-	-
Materials	607.9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	585.9	-	-	-	-	-	585.9	22.0	-	22.0	-	-	-	-	-	-	-	-
Subcontracts	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Special Equipment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Travel (non-Add)	26.4	-	-	-	-	1.3	-	-	1.3	-	-	-	-	-	-	-	-	-	-	-	-	-	6.0	-	6.0	-	19.1	19.1	-	-	-	-	-
Other Costs	108.0	-	-	-	-	37.2	-	-	37.2	-	-	-	-	-	-	58.1	-	-	-	-	-	58.1	12.7	-	12.7	-	-	-	-	-	-	-	-
TOTAL Phase C/D (Langley)	980.5	-	-	-	-	98.4	-	10.0	108.4	-	-	-	-	3.2	3.2	750.9	-	-	-	-	-	750.9	61.7	8.4	70.1	5.7	12.5	18.2	5.9	7.7	7.7	8.4	29.7
Total B/C/D (Langley)	1,175.5	-	-	-	-	115.6	-	19.0	134.6	-	2.6	3.2	-	6.3	12.1	906.0	-	-	-	-	-	906.0	61.7	11.6	73.3	7.3	12.5	19.8	5.9	7.7	7.7	8.4	29.7

Program Totals (Langley, CU, PSI)

ProgramTotal Phase-B	823.3	3.2	18.6	11.9	7.1	17.2	36.0	13.6	107.6	127.9	47.5	45.5	17.3	57.6	295.8	179.4	54.6	15.6	67.6	12.0	11.6	340.8	9.8	61.6	71.4	4.7	3.0	7.7	-	-	-	-	-
ProgramTotal Phase-C/D	4,108.9	11.3	62.3	42.1	24.4	98.4	69.7	21.8	329.9	313.4	31.7	110.4	59.3	88.8	603.6	780.1	198.5	75.2	446.8	210.2	246.9	1,957.6	470.1	410.3	880.4	30.7	224.9	255.6	12.1	25.5	20.0	24.1	81.7
Grand Total Phase-B/C/D	4,932.2	14.4	80.9	54.1	31.5	115.6	105.6	35.4	437.5	441.3	79.2	156.0	76.6	146.3	899.4	959.5	253.1	90.8	514.4	222.2	258.5	2,298.5	479.9	472.0	951.8	35.4	227.9	263.3	12.1	25.5	20.0	24.1	81.7

CERTIFICATION REGARDING DRUG-FREE WORKPLACE REQUIREMENTS (GRANTS/COOPERATIVE AGREEMENTS)

A. The grantee certifies that it will provide a drug-free workplace by:

(a) Publishing a statement notifying employees that the unlawful manufacture, distribution, dispensing, possession or use of a controlled substance is prohibited in the grantee's workplace and specifying the action that will be taken against employees for violation of such prohibition;

(b) Establishing a drug-free awareness program to inform employees about --

(1) The dangers of drug abuse in the workplace;

(2) The grantee's policy of maintaining a drug-free workplace;

(3) Any available drug counseling, rehabilitation, and employee assistance programs; and

(4) The penalties that may be imposed upon employees for drug abuse violations occurring in the workplace;

(c) Making it a requirement that each employee to be engaged in the performance of the grant be given a copy of the statement required by paragraph (a);

(d) Notifying the employee in the statement required by paragraph (a) that, as a condition of employment under the grant, the employee will --

(1) Abide by the terms of the statement, and

(2) Notify the employer of any criminal drug statute conviction for a violation occurring in the workplace no later than five days after such conviction;

(e) Notifying the agency within ten days after receiving notice under subparagraph (d)(2) from an employee or otherwise receiving actual notice of such conviction;

(f) Taking one of the following actions, within 30 days of receiving notice under subparagraph (d)(2), with respect to any employee who is so convicted --

(1) Taking appropriate personnel action against such an employee up to and including termination; or

(2) Requiring such employee to participate satisfactorily in a drug abuse assistance or rehabilitation program approved for such purposes by a Federal, State, or local health, law enforcement, or other appropriate agency;

(g) Making a good faith effort to continue to maintain a drug-free workplace through implementation of paragraphs (a), (b), (c), (d), (e), and (f).

B. The grantee shall insert in the space provided below the site(s) for the performance of work done in connection with the specific grant:

Place of Performance (Street address, city, county, state, zip code):

University of Colorado, Boulder, Colorado, 80309

Signature of Responsible University Official and Date:

D Kassoy 03/30/95

Typed Name and Title:

David R. Kassoy, Associate Vice Chancellor for Academic Affairs

Title/Identification of Applicable Research Proposal:

Micron Accuracy Deployment Experiment (MADE) (Renewal of NASW-4873)

NASA Proposal No.: ________________

Title: Micron Accuracy Deployment Experiment (MADE)

Principal Investigators: Lee Peterson

CERTIFICATION REGARDING DEBARMENT, SUSPENSION AND OTHER RESPONSIBILITY MATTERS -- PRIMARY COVERED TRANSACTIONS

(1) The prospective primary participant certifies to the best of its knowledge and belief, that it and its principals:

(a) Are not presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency;

(b) Have not within a three-year period preceding this proposal been convicted of or had a civil judgment rendered against them for commission of fraud or a criminal offense in connection with obtaining, attempting to obtain, or performing a public (Federal, State or local) transaction or contract under a public transaction; violation of Federal or State antitrust statutes or commission of embezzlement, theft, forgery, bribery, falsification or destruction of records, making false statements, or receiving stolen property;

(c) Are not presently indicted for or otherwise criminally or civilly charged by a governmental entity (Federal, State or local) with commission of any of the offenses enumerated in paragraph (1)(b) of this certification; and

(d) Have not within a three-year period preceding this application/proposal had one or more public transactions (Federal, State or local) terminated for cause or default.

(2) Where the prospective primary participant is unable to certify to any of the statements in this certification, such prospective participant shall attach an explanation to this proposal.

CERTIFIED BY:

Signature | 03/30/95 Date

David R. Kassoy
Typed Name

Associate Vice Chancellor for Academic Affairs
Title

The University of Colorado at Boulder
Institution

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13. ABSTRACT *(Maximum 200 words)*

This report documents a Phase A In-STEP flight experiment development effort. The objective of the experiment is to deploy a portion of a segmented reflector on the Shuttle and study its micron-level mechanics. Ground test data are presented which projects that the on-orbit precision of the test article should be approximately 5 microns. Extensive hardware configuration development information is also provided.

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